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Highly Accurate Measurement of Projectile Trajectories

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DEPARTMENT OF DEFENCE

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ABSTRACT

A method has been developed for making very accurate position and angular attitude measurements over the trajectory of gun launched, fin stabilised weapons. The method has been extensively used for free flight testing of weapon models. This report describes the on board instrumentation, the range instrumentation and the experimental procedure used to carry out the trajectory measurements. The post trials processing of the camera records is also described and a brief account given of the analysis used to derive vehicle aerodynamics.

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Executive Summary

Research into flight characteristics of various aerial weapons requires a knowledge of the way the weapon will behave when travelling through the air. When such a weapon is released from an aircraft it is obviously important to know where it will land. Trajectories of air to ground weapons are generally measured by observing actual drops of the weapon, by computer simulation, or by conducting wind tunnel and gas gun launch trials on scale models.

Two gas guns operated by DSTO are situated at Edinburgh and Port Wakefield, the former for subsonic launching and the latter for transonic and supersonic launching. To accommodate various size weapons, light weight foam and wood sabots conforming to the size of the gun bore are used to enclose the test vehicle. The test vehicle itself contains instrumentation to operate optical strobe units, one at the nose and often, one at the tail. The instrumentation is 'g' hardened in order to withstand launch accelerations up to 3000 'g' at the maximum launch velocity.

Trials are carried out at night. Ballistic cameras are used to record flashes from strobe units installed in the model. Camera shutters are operated remotely, being opened just before launch and closed shortly after impact. Reference lights at known positions are operated remotely during the flight to provide orientation of the film records during subsequent analysis of the camera records. The positions of the cameras and reference lights are accurately known by previous survey to within 0.01m. An accurate measuring device is used to measure the positions of the images on the films from various cameras to determine the trajectory for the model with the help of a computer. From this trajectory and the time intervals between each image registration, flight characteristics such as drag coefficient can be measured and predictions made about the behaviour of the full scale weapon by well tried methods.

The technique has been extensively used in the determination of the Mk80 series bomb drag characteristics. These bombs form part of the Royal Australian Air Force F-111C strike aircraft stores inventory. As part of the Avionics Update Program armament modelling associated with this aircraft, results from trials carried out with models of the store have been used to form a data base for use by the aircraft's on-board ballistic computer.

Contents

1. Introduction

Free flight testing of projectile designs is required to verify the accuracy of estimates made of effects due to the change in size from wind tunnel model to larger scale projectile, and of the effects arising from the flight dynamic behaviour of the projectile.

AMRL has a number of smooth bore gas-operated guns, sited on two aeroballistic ranges, located adjacent to the RAAF Base at Edinburgh and at the Army P&EE Establishment at Port Wakefield, which are used to launch a wide variety of fin stabilised projectile models for this purpose. The Edinburgh range uses principally a 384 mm bore gas gun for launching models at low subsonic launch velocities, while the Port Wakefield range uses a 265 mm gun for launches at transonic and supersonic velocities. Considerable variation in projectile model size can be accommodated by enclosing the model in cylindrical sabots conforming to the gun bore. The sabot separates from the model upon leaving the muzzle, by the action of aerodynamic drag forces, and falls behind due to high drag to weight ratio.

The gas guns have a number of advantages, compared to more conventional guns, for the launching of projectile models. Launch accelerations are less severe from the gas guns, leading to increased survivability of the projectile model and on-board instrumentation. Muzzle velocities up to 440 ms^{-1} are achievable from the 265 mm gun, with a corresponding peak launch acceleration of 3,000 'g'. In comparison, for example, the Army 105 mm M2A2 howitzer produces, at the same muzzle velocity, a peak launch acceleration of 15,000 'g'. As a result, there are less design constraints on the projectile model and on the design and packaging of the on-board instrumentation.

There are also generally less restrictions on the operation of the gas guns, as safety considerations relating to the handling of explosives ordnance do not apply. In addition, the guns and gun ranges are operated and maintained by DSTO, affording more flexibility to firing programs due to their greater availability. The gas guns are more fully described at reference 1.

In the technique described in this report, models are equipped with front and rear mounted optical strobe units. The units consist of suitably housed gas discharge tubes and associated electronics driving circuit, which produce a high intensity, short duration, fixed frequency flash during flight at simultaneous time intervals.

Trials are carried out at night. A number of ballistic cameras (reference 2) are located at intervals on either side of the range and offset to one side. The camera shutters are opened just prior to launch, and closed again after impact, resulting in a series of image registrations on the camera films. This data is then processed to obtain information relating to the model flight performance. Figure 1, a positive film from a 35 mm camera, shows part of the photographic trace of a projectile model (equipped with a nose strobe unit only).

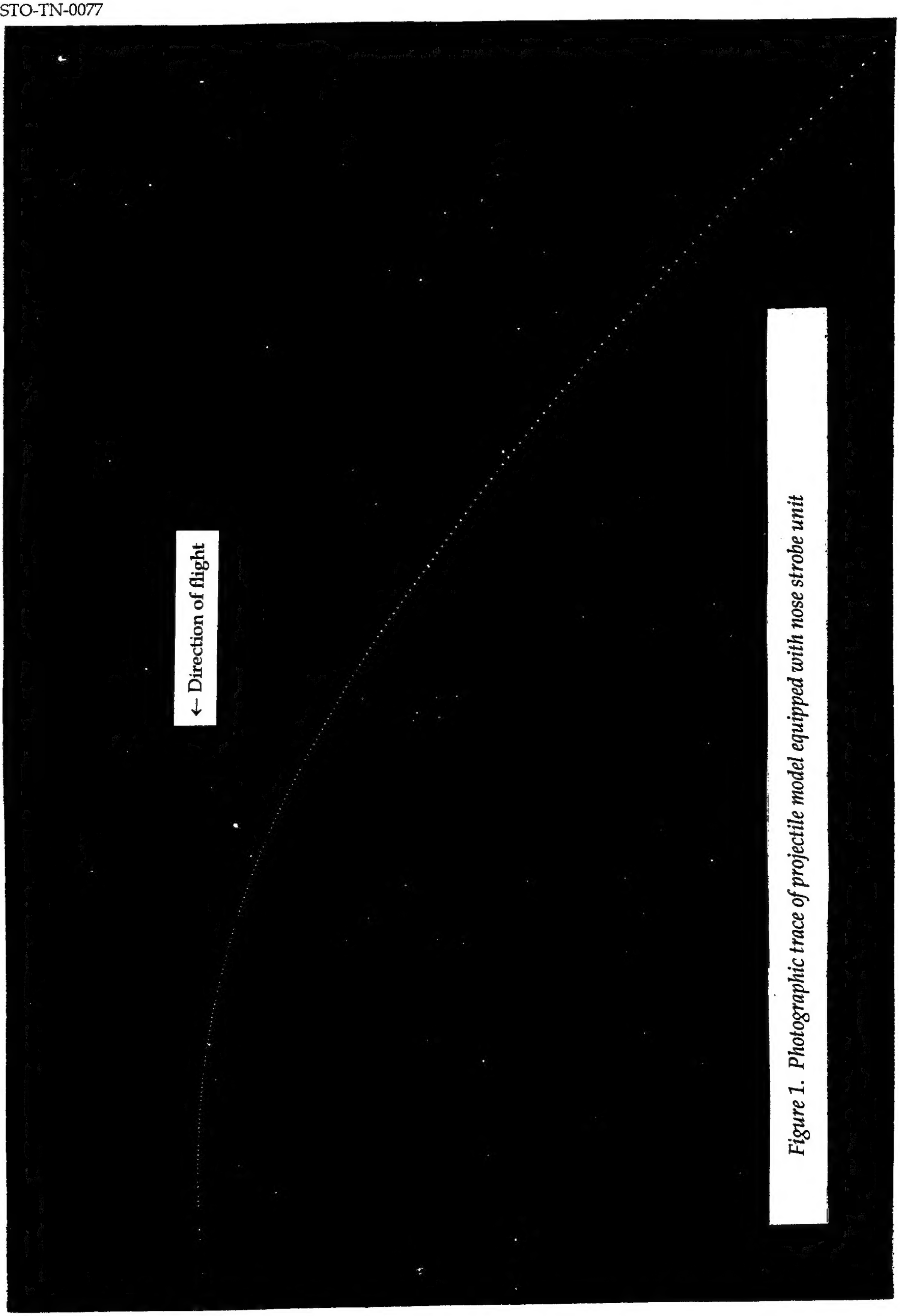


Figure 1. Photographic trace of projectile model equipped with nose strobe unit

In addition to the camera positions, a number of reference light (RL) array positions are also provided. The arrays are operated during the projectile's flight, and are used to orient the cameras with respect to the range axes. The cameras and RL arrays can be either locally or remotely operated at both ranges. The positions of the arrays and the optical centres of the camera lenses are accurately surveyed to within 0.01 m (reference 3), and the surveyed positions used to derive the co-ordinates of the projectile for each image on the film.

This report describes the on-board and range instrumentation used, and the trials procedure followed. A brief description of the photographic film reading procedure is included, together with some sample trials results, as well as a discussion of the effectiveness of the technique and possible future extension of its capabilities.

2. Instrumentation

This section describes the on-board instrumentation, consisting of the strobe tubes, electronics package, inertia switch assembly and power source. It also describes the circuit used to detect and measure the flash repetition rate prior to launch and after recovery, and the range instrumentation, including the RL arrays and associated control systems, but excluding the ballistic cameras.

2.1 On-board instrumention

The various components comprising the on-board instrumentation are described below. A typical test vehicle installation is shown in Figure 2. The test vehicle in this case is a half scale model of a Mk82 bomb.

The models used in trials vary in size. They are designed at AMRL and manufactured under contract. During the design process provision is made for housing of the on-board instrumentation. There are usually no constraints on its location, subject to centre of gravity requirements of the model being met.

2.1.1 Strobe tubes

Xenon gas filled quartz tubes, type VQXS 52P, manufactured by the French company Verre-et-Quartz, are used in this application. The helical construction of this tube type allows most efficient use of available space within the projectile model. When triggered, a light pulse of approximately 150 μs duration is produced. The tubes are rated at 10 Joules in still air and less when encapsulated. However they are deliberately over-driven to approximately 25 Joules, to produce the required light intensity for ranges in excess of 1 km. At such an output, they have a lifetime of 3-4 minutes, compared with an average flight time of less than 30 seconds.

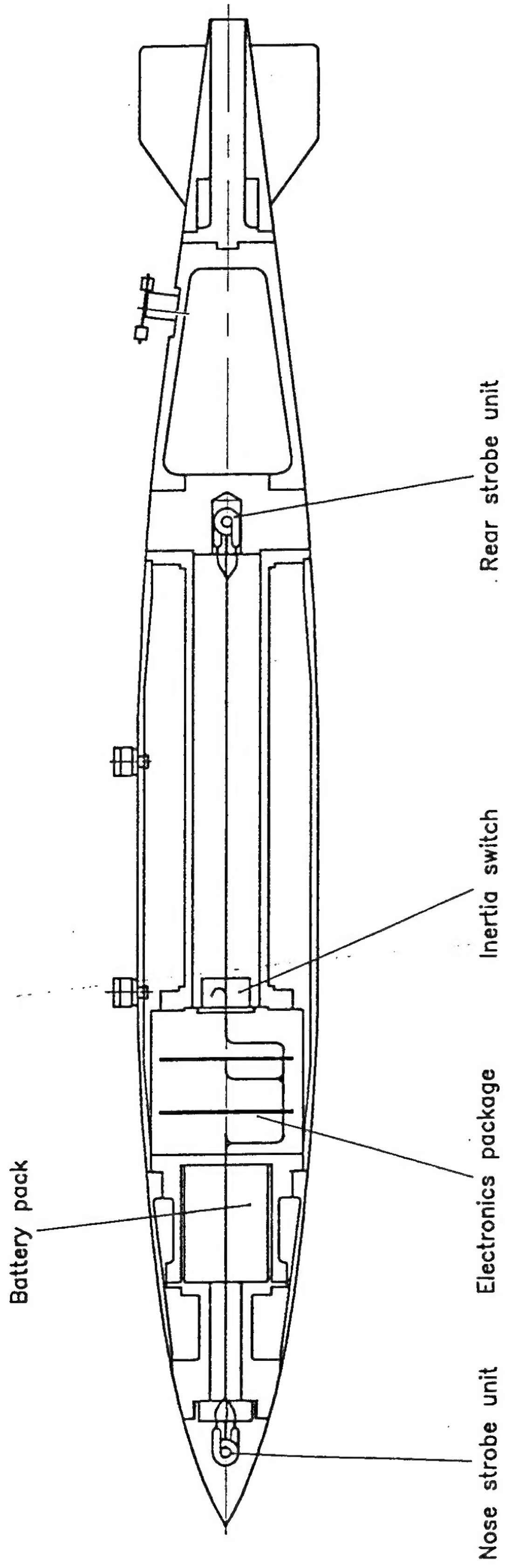


Figure 2. Typical Instrumented Test Vehicle

The tubes are encapsulated in transparent sylgard resin, in housings manufactured from polycarbonate, which although not as transparent as materials such as perspex and some epoxy resins, has sufficient mechanical strength to withstand gas gun launches.

The sylgard is preferred, as encapsulation in some epoxy resins can lead to cracking of the tube during the curing process. In addition, the sylgard is slightly flexible, affording a degree of cushioning to the tubes against the initial peak launch accelerations.

2.1.2 Electronics Package

The following sections describe the construction of the electronics package, encapsulation methods, and schematic circuit operation.

2.1.2.1 General Assembly

The electronics package consists of an assembly of circular printed circuit cards stacked within a housing designed to conform to the internal dimensions of the test vehicle. In small test vehicles where there are constraints on the available space, smaller diameter cards must be used, resulting in more cards being required in the stack to accommodate the circuitry. In the larger test vehicles larger diameter cards can be used, resulting in less cards in the stack. A typical arrangement is shown in Figure 3.

2.1.2.2 Encapsulation

Until recently, the printed circuit card assembly was encapsulated in an epoxy resin, usually araldite, to inure it against launch accelerations. This process was carried out under vacuum to eliminate the possibility of air bubbles being trapped in the package.

While epoxy resin is a low cost encapsulant with the required strength for this application, it does suffer from the disadvantage of greatly reducing accessibility to components and wiring, with the resultant difficulty in tracing and rectifying any faults which may develop after encapsulation. In fact, the resin itself may sometimes be responsible for inducing faults within the larger packages used in some applications, due to the stress placed upon components and circuit boards by the heat and expansion generated during the curing process.

An alternative method of encapsulation, which uses silica glass beads as the packaging media, has recently been developed and successfully tested, and is now in routine use. The silica glass beads are far less likely to induce faults, and any which may develop, for whatever reason, can be attended to simply by removal of the beads to permit access.

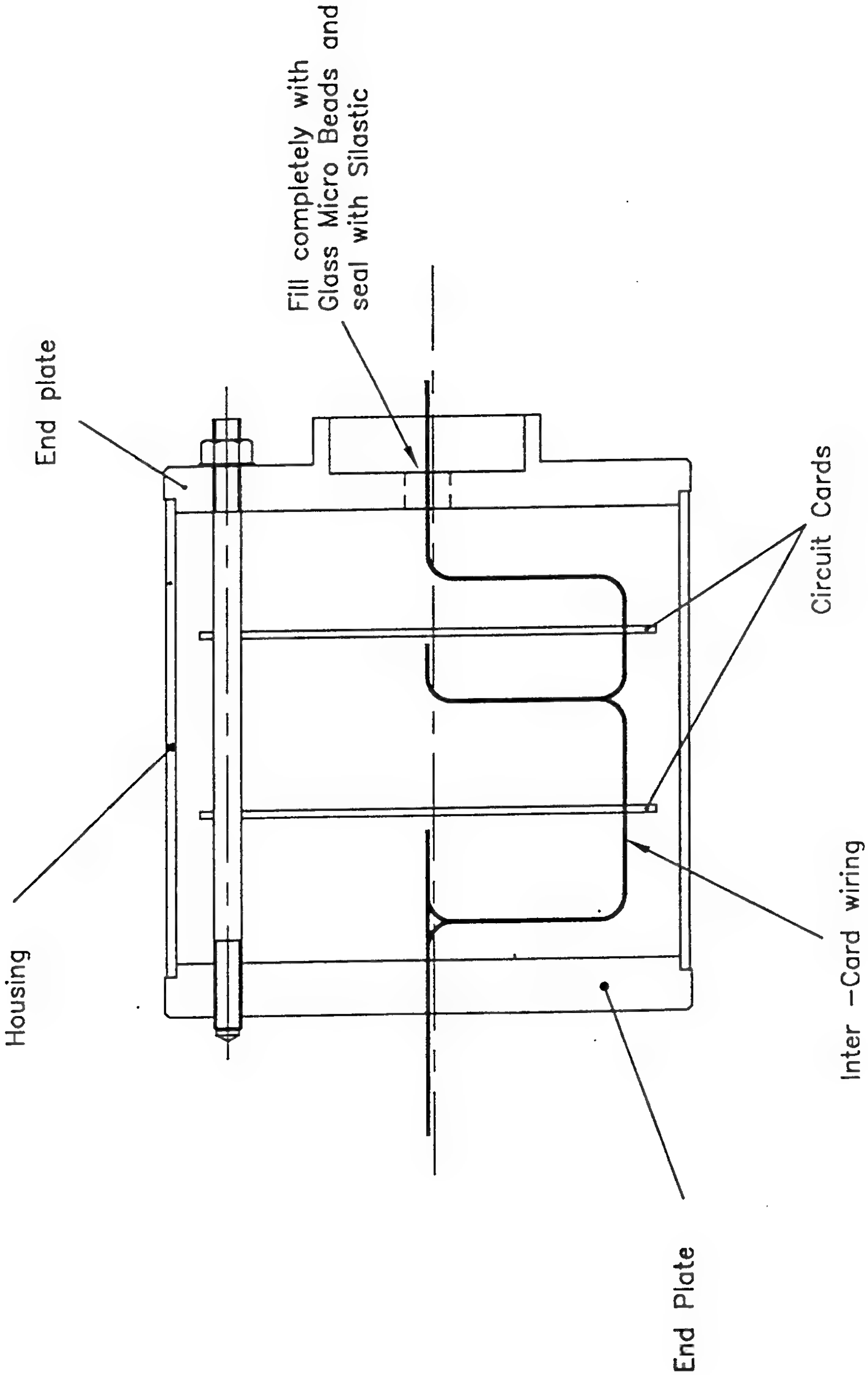


Figure 3. Electronics Package

The important criteria which need to be adhered to when using this technique are complete penetration of the volume of the package by the beads, and suitable packing and restraining of the beads within the package. Penetration can be assisted by the use of small diameter beads (45-90 microns), a vibration shaker table, and by the provision of sufficient space between the printed circuit cards and walls of the housing, and between the cards themselves.

Precautions are also taken during storage and handling to minimise absorption of moisture by the beads, which by nature are hygroscopic. A high moisture content can lower the dielectric strength of the beads and increase stray capacitance levels on the circuit boards. This can lead to an attenuation of the high voltage levels required to drive the tubes and result in intermittent operation.

The beads are stored in a dry environment and a dessicant such as silica gel is used to maintain low moisture levels. Care is also taken during the packaging process to avoid exposure to excessive moisture.

2.1.2.3 Description of operation

A block diagram of the electronics package is shown in Figure 4.

The Regulator, the schematic circuit of which is shown in Figure 5a, provides a regulated output voltage to the DC-DC Converter and Clock Generator. It provides full regulator operation for an input-output differential as low as 130 mV, at load currents up to 3 A, to maximise battery pack efficiency. The output voltage, determined by the ratio of R4:R3, is set to 14 V.

The DC-DC Converter, shown in Figure 5b, generates the voltage, 300-350V, required by the holding capacitors in the Storage circuit, Figure 5c. It is driven by outputs A and B of regulating pulse width modulator N1 in the Clock Generator section, shown in Figure 5d. These outputs are rectangular waveforms with a 50% duty cycle at a frequency of approximately 30 kHz, and are 180° out of phase.

N1 also provides the nominal 50 kHz clock input (oscillator output, pin 4), and the supply voltage (pin 16) for the Frequency Divider circuit, Figure 5e, where counter N1 provides a number of selectable output frequencies, used to set the flash rate of the strobe units. A frequency between 25 and 30 Hz is usually chosen, as it provides an adequate sampling rate without cluttering the camera film with too many images.

The pulse output from this circuit gates thyristor V1 in the Trigger circuit, Figure 5f, causing capacitor C1, whose voltage is derived from the Storage circuit, to discharge through the primary of transformer T1. This results in a 6 kV pulse on T1 secondary, triggering both tubes within a time interval of a few nanoseconds, which can be taken as being simultaneous as far as registration of the images on the camera film is concerned.

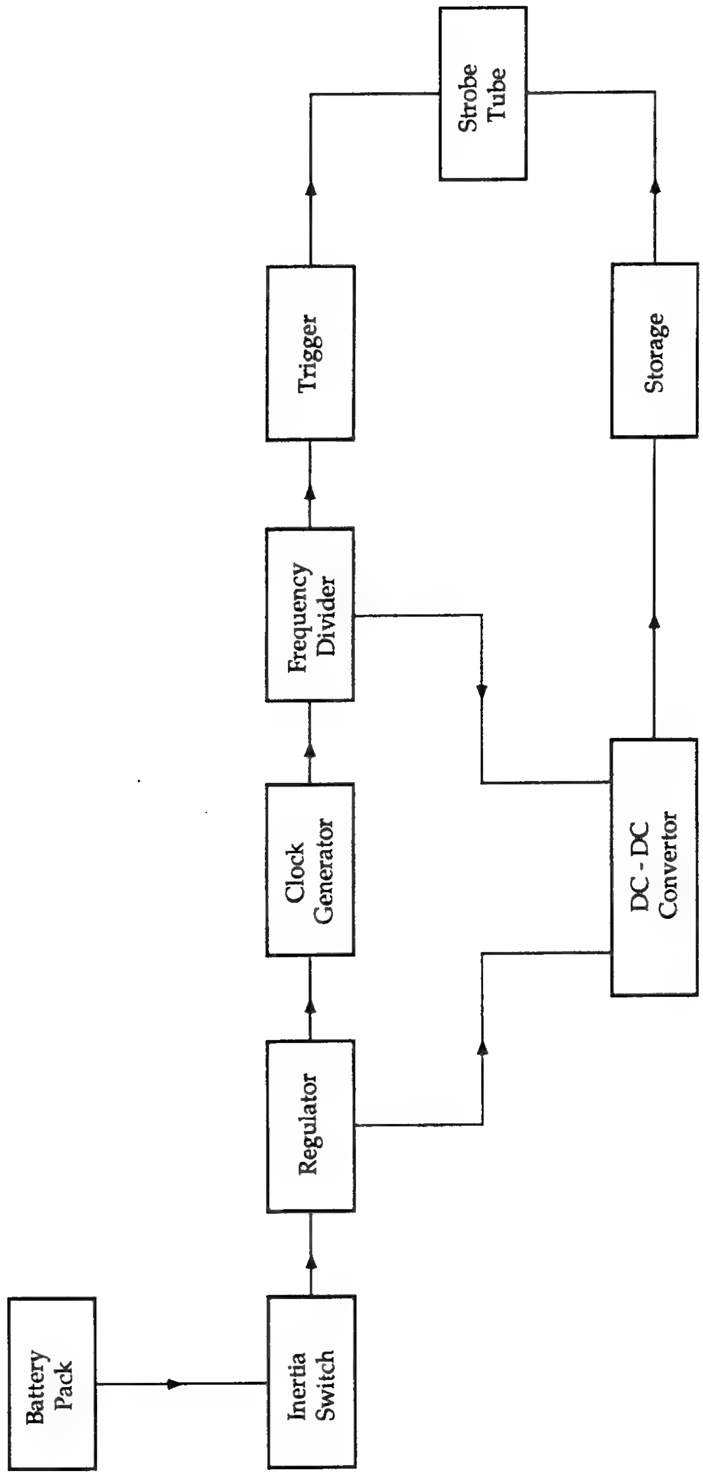


Figure 4. Electronics - Block Diagram

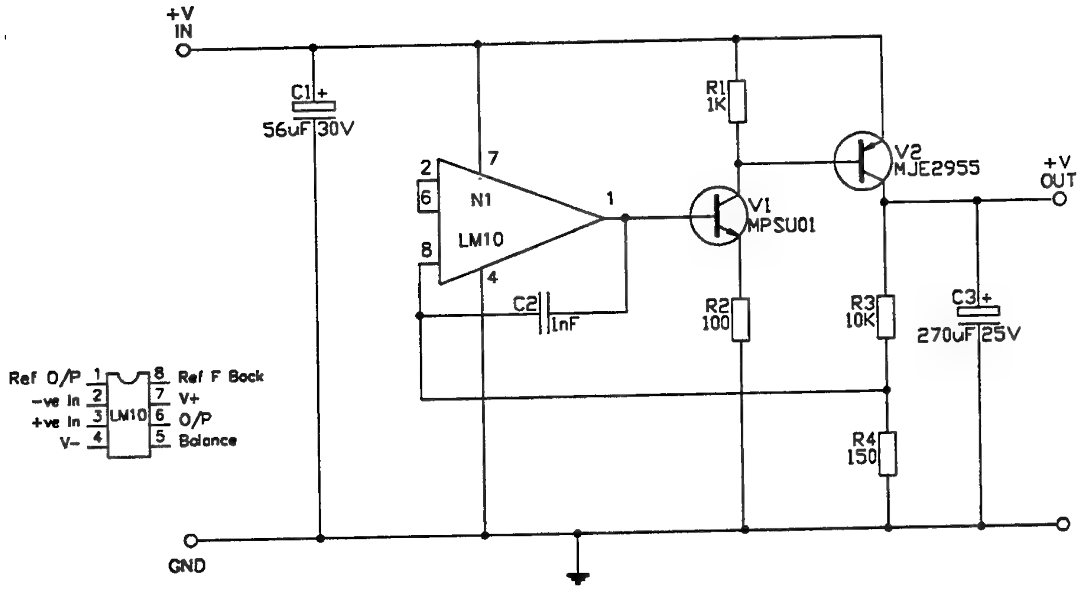


Figure 5a. Regulator

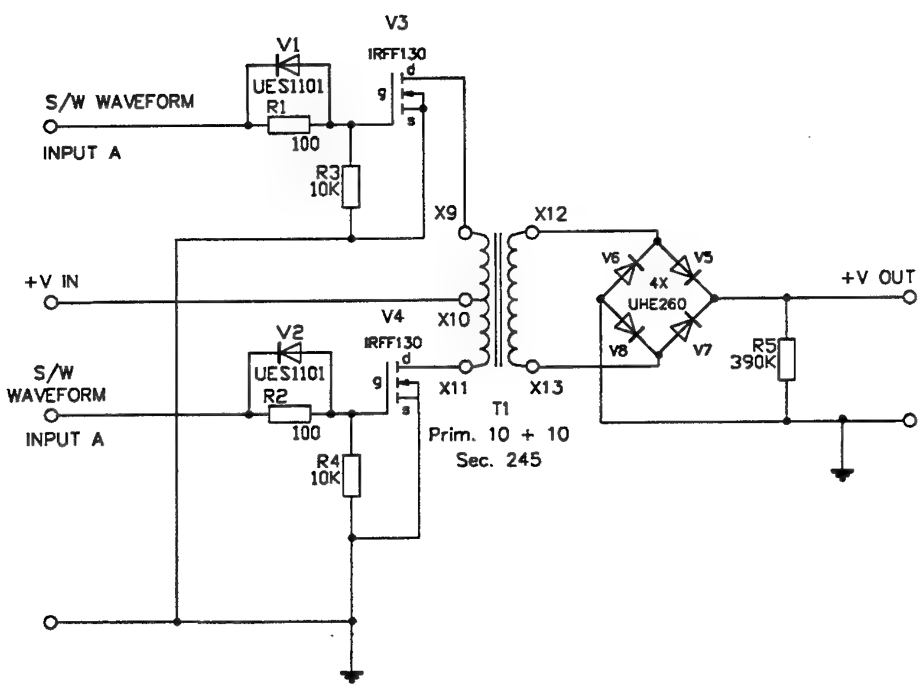


Figure 5b. DC-DC Converter

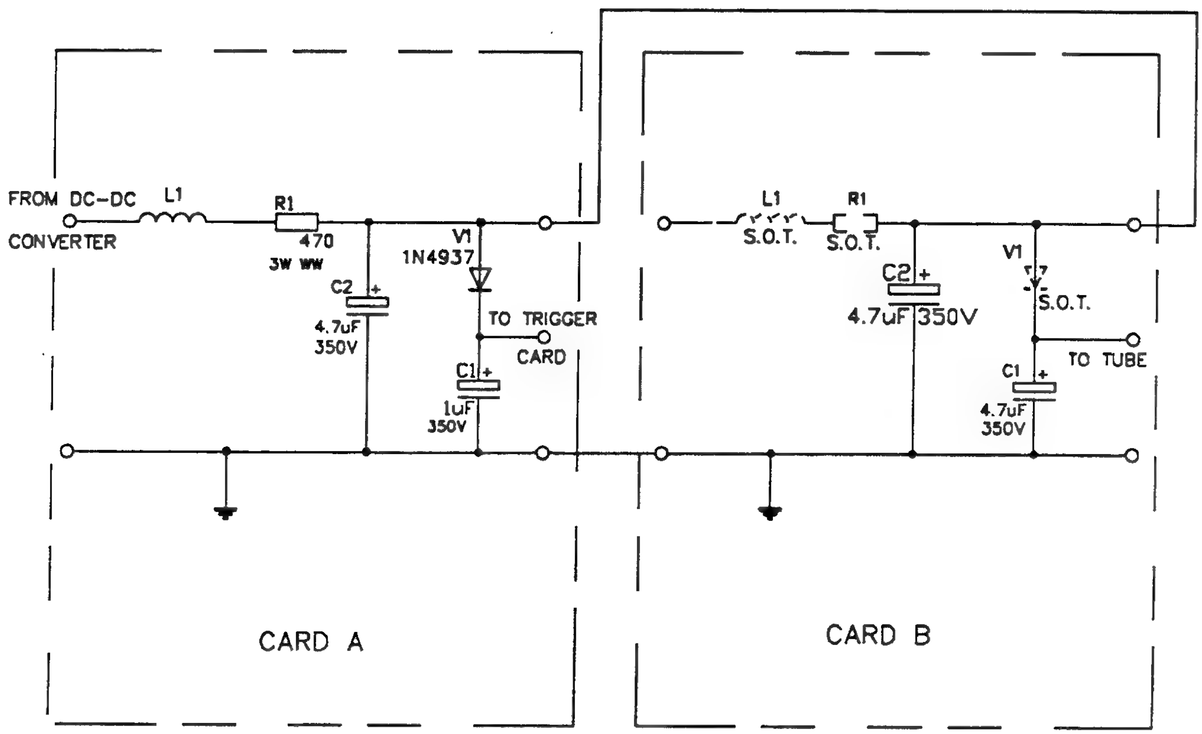


Figure 5c. Storage

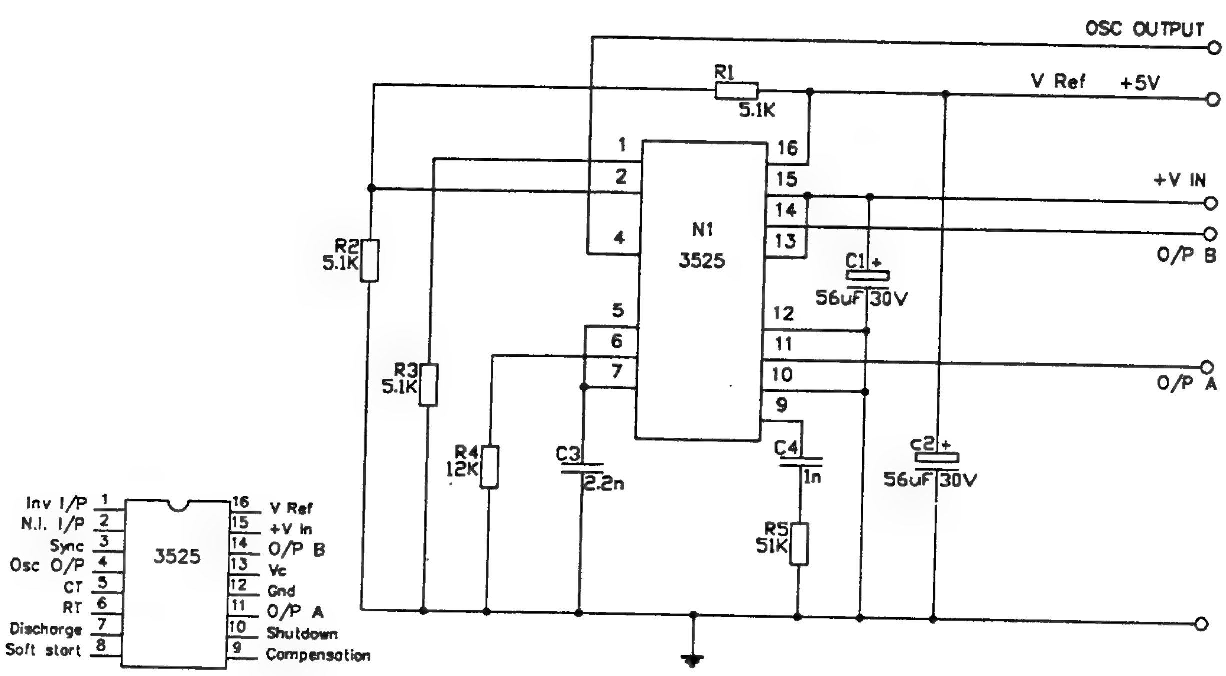


Figure 5d. Clock Generator

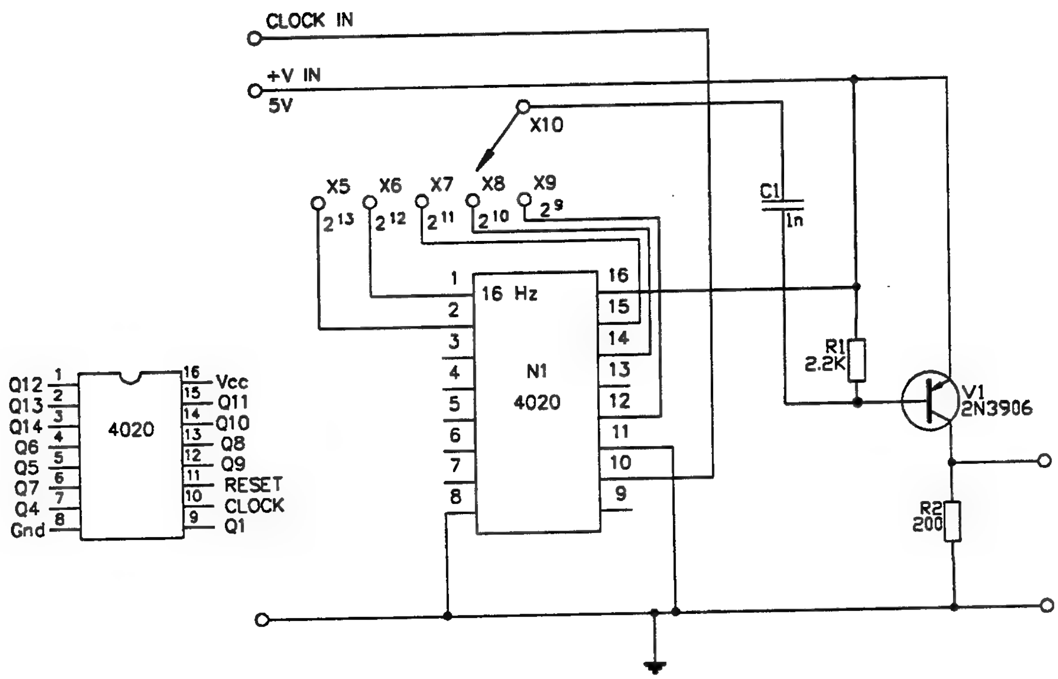


Figure 5e. Frequency Divider

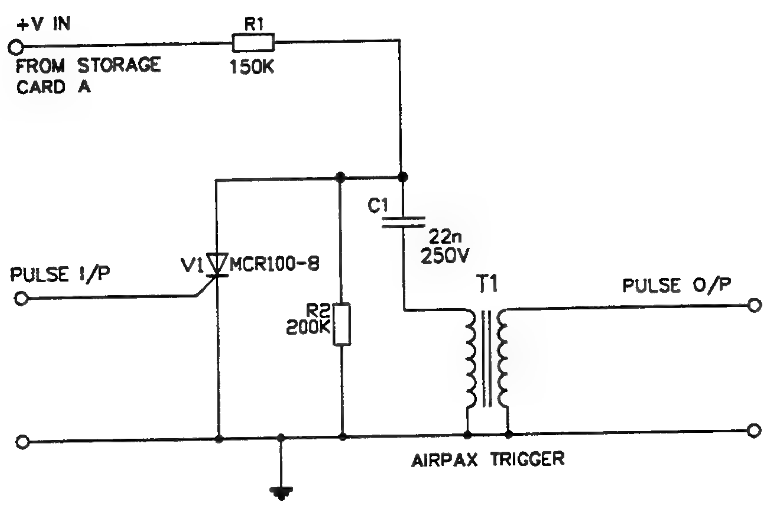


Figure 5f. Trigger

The oscillator output frequency of N1 in the Clock Generator section is determined by external timing components R4, a metal film ± 1% tolerance resistor, and C3, a ceramic dielectric style CK05 ± 10% capacitor. Consequently there can be a worst case ± 11% variation in the flash rate between packages. This is not a problem, however, as long as the flash rate of each package is known prior to the trial being carried out. The flash rate of each package can be considered as being constant throughout the short duration of flight.

2.1.3 Power Source

For reliable operation, with particular regard to the trigger voltage required for the tubes not to misfire, a supply voltage (from the Regulator output) of 13 - 14 V with the tubes operating is considered optimum. At this voltage, the electronics package and tubes draw a current of approximately 3.5 A average.

To meet this requirement, a battery pack consisting of two banks - each bank formed by four cells connected in parallel - of 9 V alkaline dry cells connected in series, is provided. A load test was carried out on the battery pack with both tubes operating, with the results as shown in Figure 6. As can be seen from the graph, the battery pack terminal voltage is 14 V initially, falling to 13 V after about 30 seconds. This compares favourably with the maximum time intervals, during which the model is within the instrumented part of the range of 15 seconds. (It should also be pointed out that the tube flash rate is constant over this voltage range).

An extrapolation of the graph reveals that the terminal voltage falls below 9 V, the threshold voltage at which the tubes fail to operate, after 2.5 minutes, which is within the operating lifetime of the strobe tubes. This prevents the tubes from self destructing and, provided post-trial recovery of the projectile model can be effected, allows the strobe unit to be re-used in many instances subject to the housing still being in good condition.

2.1.4 Inertia Switch Assembly

As the time required to load, elevate and pressurise the gas guns is 10 minutes minimum, power cannot be connected to the electronics package prior to commencement of the loading procedure. Instead an inertia switch, designed to operate at 50 'g', is used to operate a self latching circuit, shown in Figure 7, at launch to start the tubes operating. The 'g' loading at which the switch operates was selected to be greater than that which may be inadvertently generated during handling of the model, and much less than the minimum peak launch acceleration of 200 'g' produced by the subsonic gas gun.

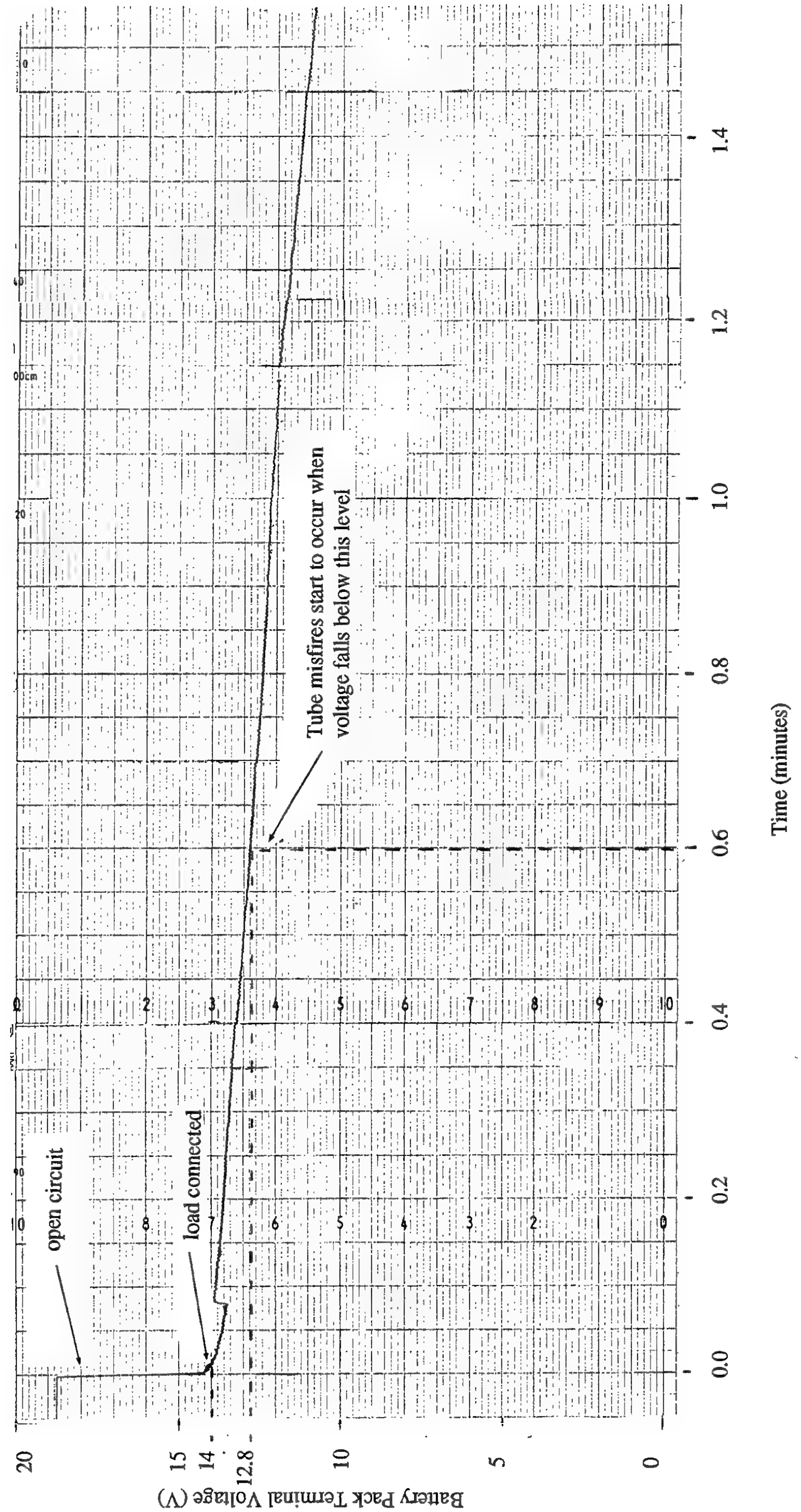


Figure 6. Battery Pack Load Test

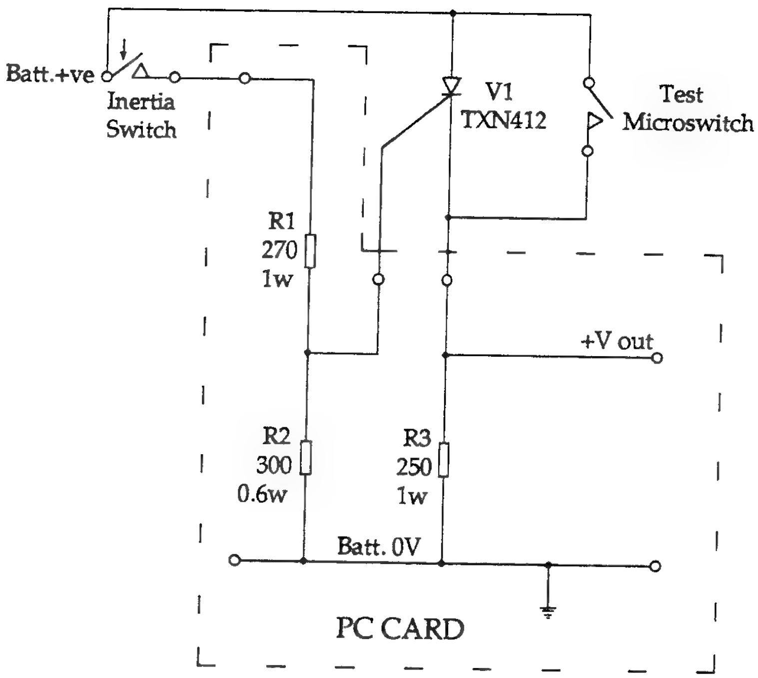


Figure 7. Inertia Switch Assembly

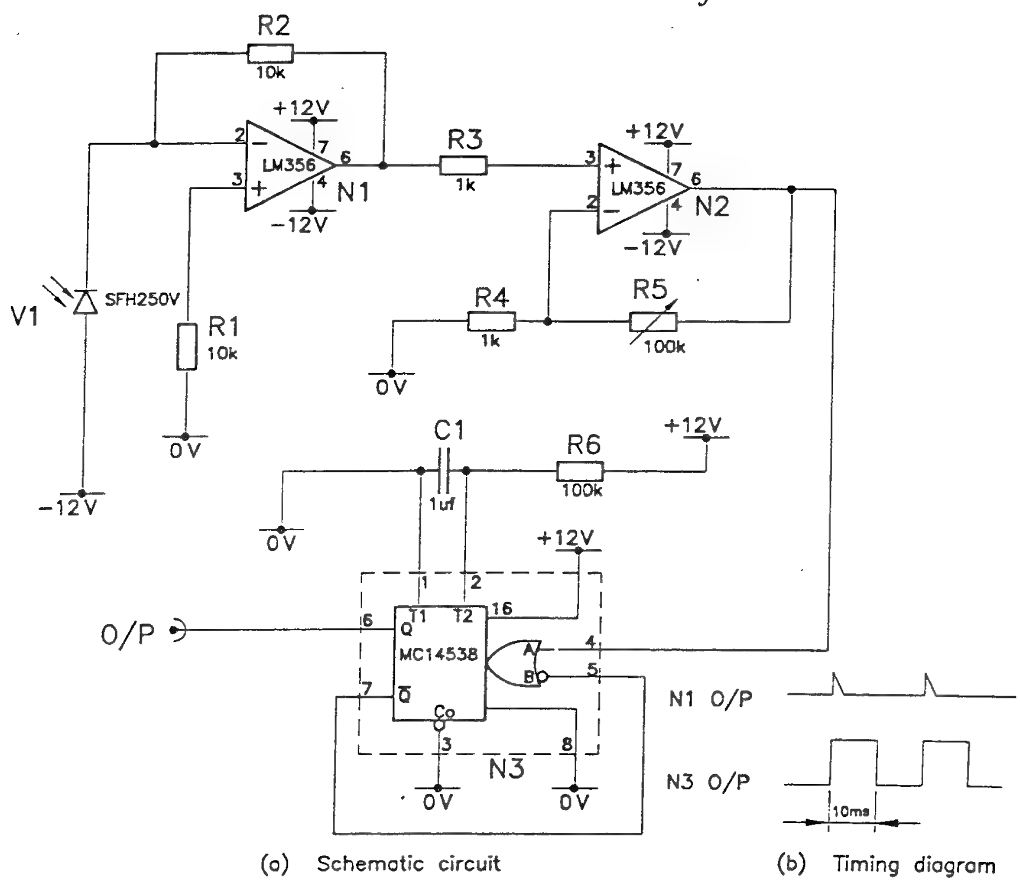


Figure 8. Flash Rate Measurement

The inertia switch assembly is provided with a channel housing a ball bearing which moves against and depresses a lever at launch, operating a microswitch which gates silicon controlled rectifier V1 on. There is sufficient hold current for V1 to remain on in the absence of gate voltage, i.e. following launch, when acceleration falls to zero. An override test switch is provided for pre-flight checks.

2.2 Flash Rate Measurement

It is necessary to accurately record the flash rate of each package, as although the flash rate of each is constant, there is some variation between packages, as discussed in section 2.1.2.3. This is done in the laboratory prior to the trial, using the circuit shown in Figure 8. The strobe pulses are detected by photodiode V1, linked by a fibre optic cable to the strobe tube. The fibre optic cable eliminates interference from the induced tube trigger voltage. The cathode of V1 is connected to amplifier N1, the output of which is applied to amplifier N2, which is configured to provide a maximum positive output voltage swing for varying input levels, ensuring reliable triggering of monostable N3.

The circuit is used in conjunction with a Nicolet 3091 digital storage oscilloscope, which records the pulses from N3 over a sufficient time interval to enable the flash rate to be determined and to check if any misfires have occurred. A record length of 2 seconds is usually selected, resulting in an oscilloscope sample interval of 0.5 ms and a resolution capability of 0.2 ms. As the pulses from V1 are typically of only 0.1 ms duration, the output pulse width of N3 is set by R6 and C1 to 10 ms, to ensure that all strobe pulses are captured by the oscilloscope.

2.3 Range Instrumentation

The range instrumentation consists of ballistic cameras, RL arrays, and associated control equipment, located at intervals along, and on either side of, the gun centre line of fire at each range. The layouts of the respective ranges, showing locations and coverage of the RL arrays and cameras, are shown in Figure 9. At both ranges the camera and RL array positioning and alignment is such that only the initial part of the trajectory is covered - projectile range is typically 4 - 5 km, depending on barrel elevation and muzzle velocity. This is sufficient for present needs, but the coverage could be extended by provision of more cameras and arrays, or repositioning of the existing equipment.

Each RL array consists of three gas discharge units which are operated just after launch, while the camera shutters are open, to produce a similar intensity and duration flash to that produced by the projectile strobe units. The array units are mounted in a horizontal line on a frame, as shown in Figure 10. The position of the central unit is accurately surveyed, while the two outboard units are used in conjunction with the central unit to provide a characteristic image on the film, to assist in distinguishing it from any other spurious images which may be present.

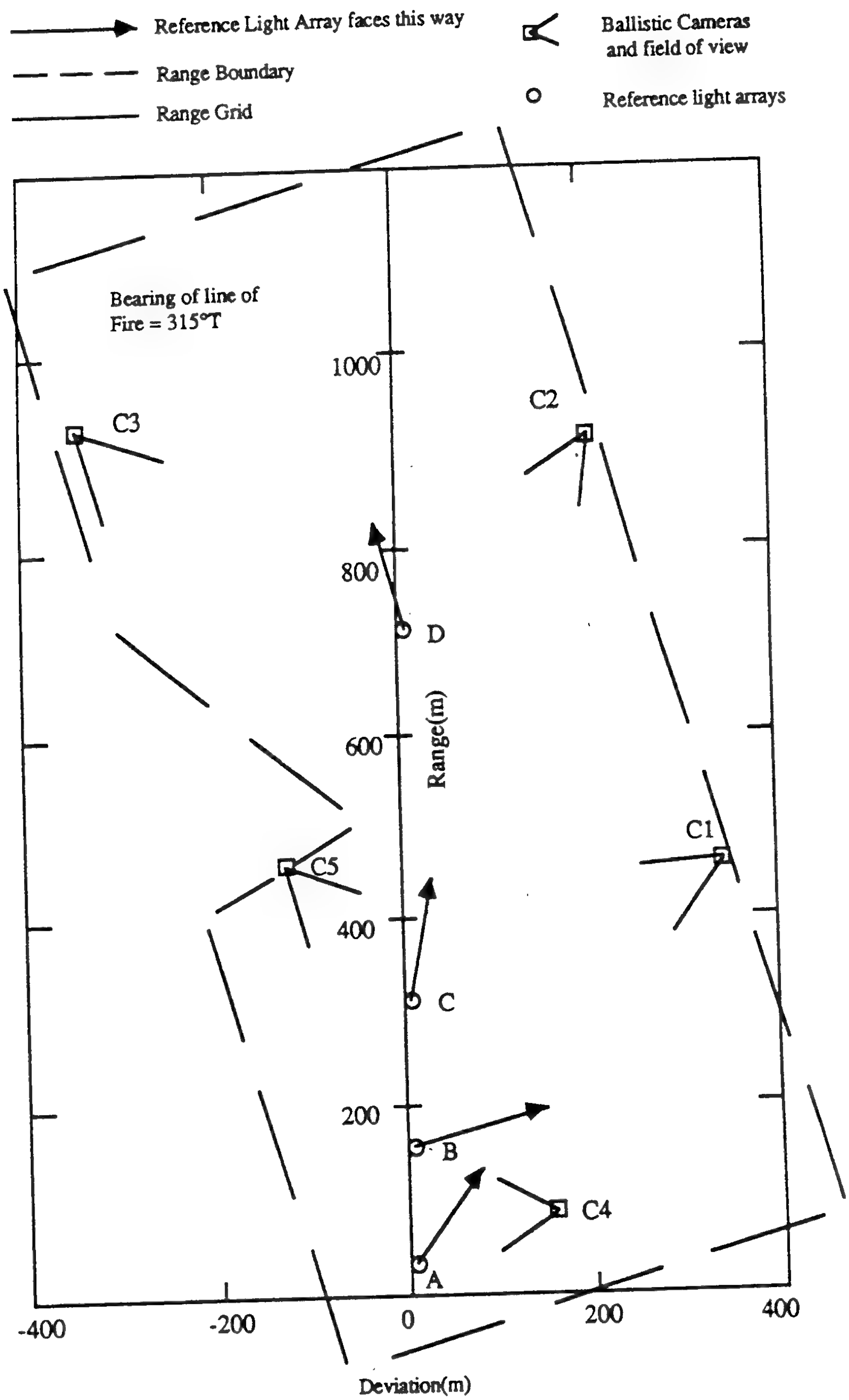
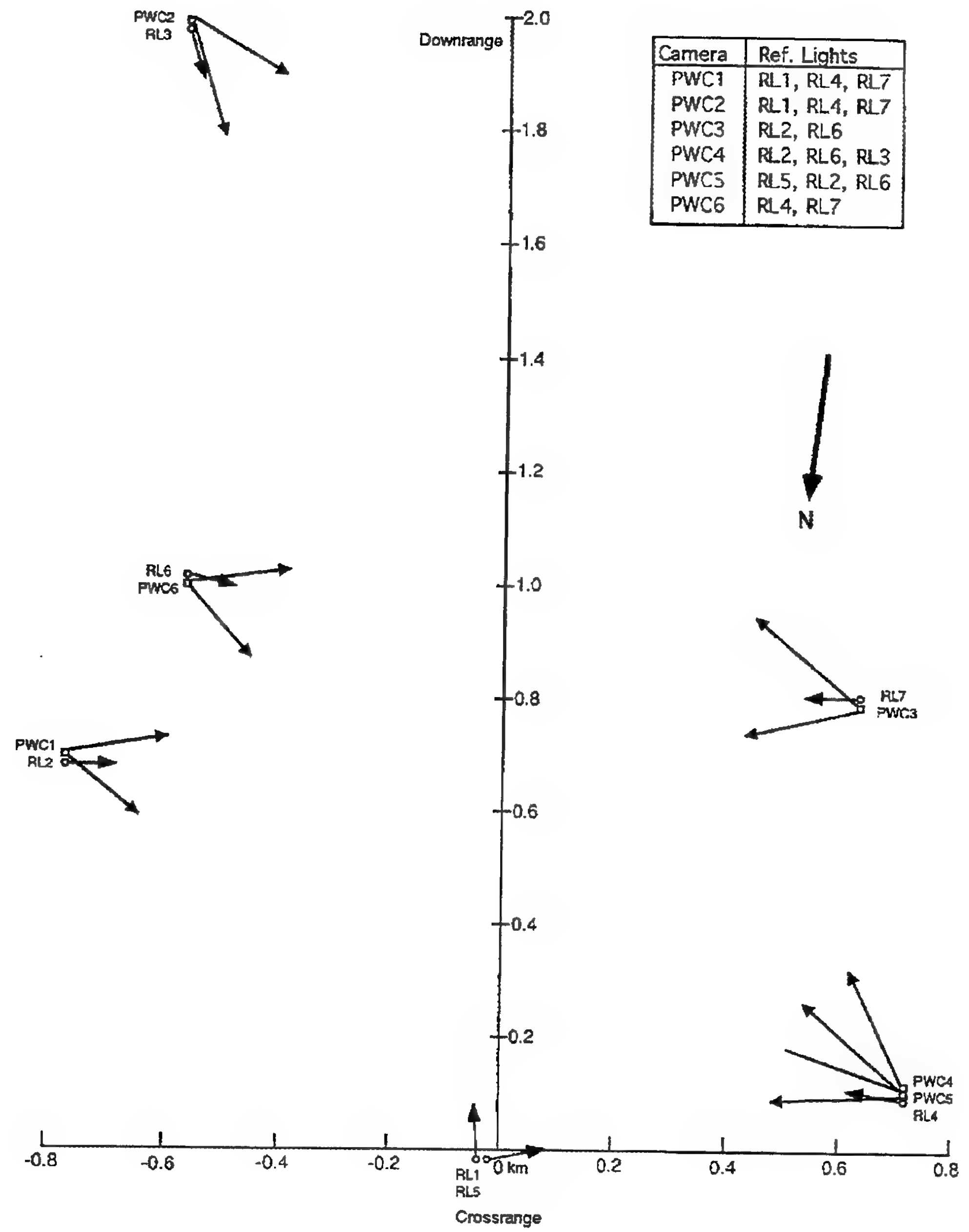


Figure 9a. Layout of Edinburgh Range



Camera	Ref. Lights
PWC1	RL1, RL4, RL7
PWC2	RL1, RL4, RL7
PWC3	RL2, RL6
PWC4	RL2, RL6, RL3
PWC5	RL5, RL2, RL6
PWC6	RL4, RL7

Figure 9b. Layout of Port Wakefield Range

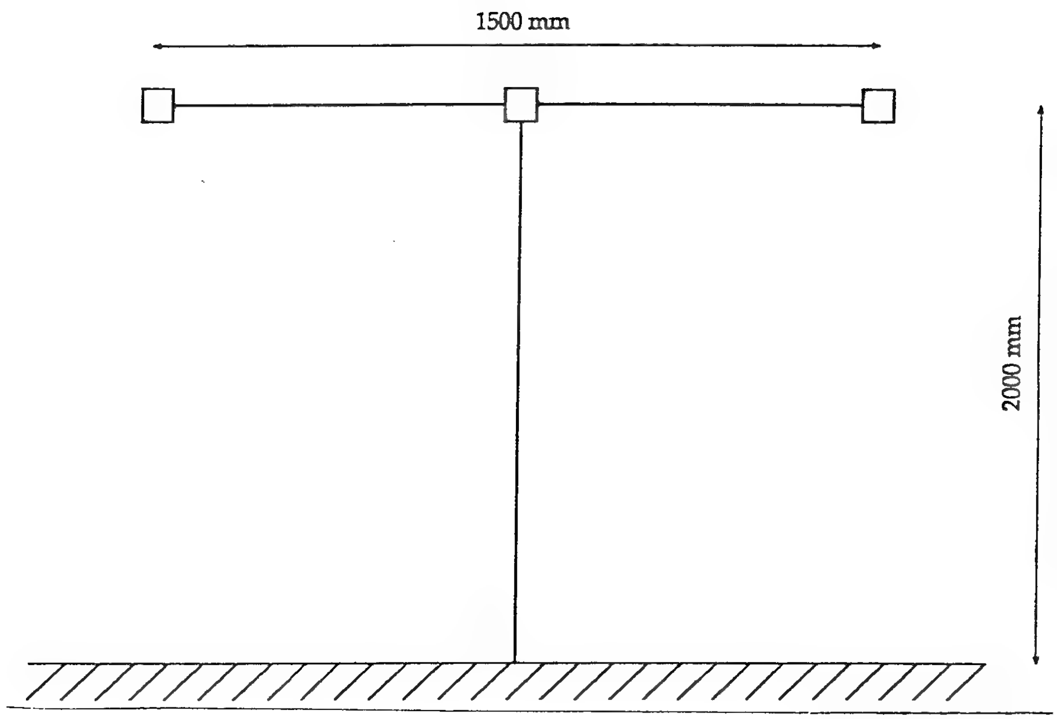


Figure 10. Reference Light Array

Each camera, the operation of which is described in detail at reference 2, has a flap shutter which is opened at launch to expose the camera film for the duration of each flight. Each camera has a fixed 50° field of view, and the cameras are oriented to provide an overlapping coverage of the projectile's flight.

The operation of the instrumentation at both ranges is described below.

2.3.1 Edinburgh Range

Landline links are provided via an underground cable between the Control Room and all camera positions except C5, enabling C1 - C4 to be operated locally at the site or remotely from the Control Room, while C5 can only be operated locally.

The underground cable terminates in an upstand at each camera position, with a cable connection from the termination to the Camera Control Unit (CCU). Remote operation is carried out by applying 12 V d.c. via the landline to the relay within the CCU which controls the opening/closing of the camera shutter. Local operation is achieved by operating the Shutter Open/Close switch on the front panel of the CCU.

Landlines are also provided to all RL array positions from the Control Room, enabling them to be remotely operated. As all arrays are located on the centre line of fire, local operation is not possible, due to safety considerations.

Each RL array site consists of a frame on which are mounted the three flash units and a DC-DC Converter unit. A sighting lamp is also located above the flash units as a backup in the event that they malfunction during a trial. There are cable connections between the DC-DC Converter unit and the RL control box, located adjacent to the frame, as well as between the RL control box and the landline termination post, and between the DC-DC Converter unit and the termination post, as shown in Figure 11.

The operation of the arrays is tested locally prior to the trial by momentarily depressing the Trigger pushbutton located on the RL control box front panel. Each operation of the pushbutton causes the three flash units to simultaneously flash once.

Due to the varying cable lengths between the control room and RL array positions, line compensation resistance is provided to ensure reliable operation of each array. It should also be noted that, unlike at the Port Wakefield Range, no indication is provided as to whether or not the equipment at the remote sites has responded to commands from the Control Room during each trial.

2.3.2 Port Wakefield Range

Until recently, there was no link between the Control Room and the remote sites at the Port Wakefield range. Unlike the situation at Edinburgh, the RL arrays are co-sited with the cameras at this range, and so can be operated locally, along with the cameras. Coupled with the fact that distances from the Control Room to the various sites are much greater here than at Edinburgh, the cost of provision of a landline or radio telemetry link was not considered to be justified while trials activities remained light.

However, a much heavier trials program led to a reassessment of the situation, and a decision was made to install a radio telemetry link between the Control Room and five of the seven remote sites, with the remaining two sites, located very close to the Control Room, connected to it by landlines.

The layout of the range, showing the location of the remote sites and the equipment at each site, is shown in Figure 12. The telemetry system consists of a Master Control Unit (MCU), located in the Control Room, and five Remote Terminal Units (RTU's), provided with outputs which control the operation of the cameras and RL arrays at each site.

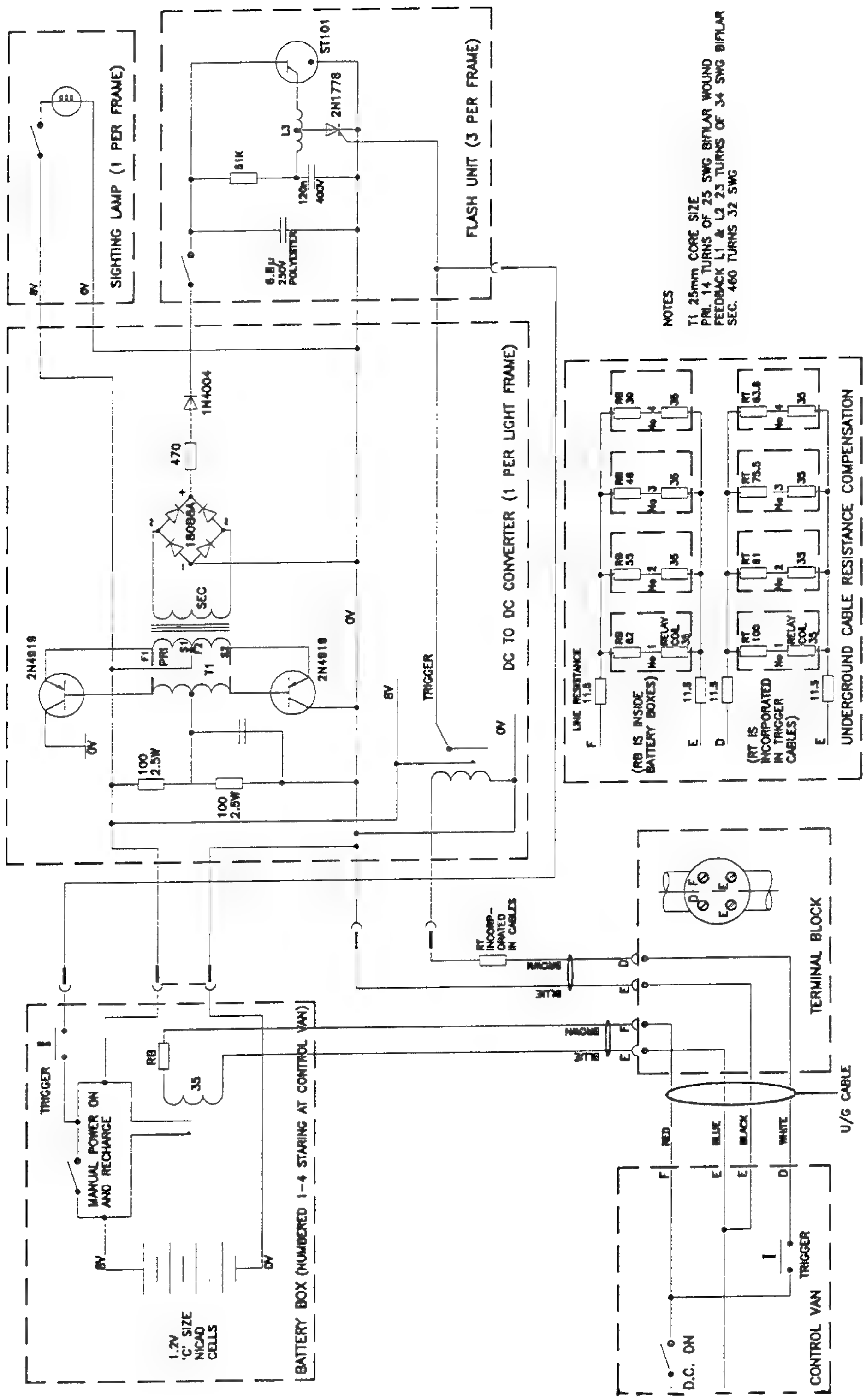


Figure 11. RL Array and associated Remote Control System

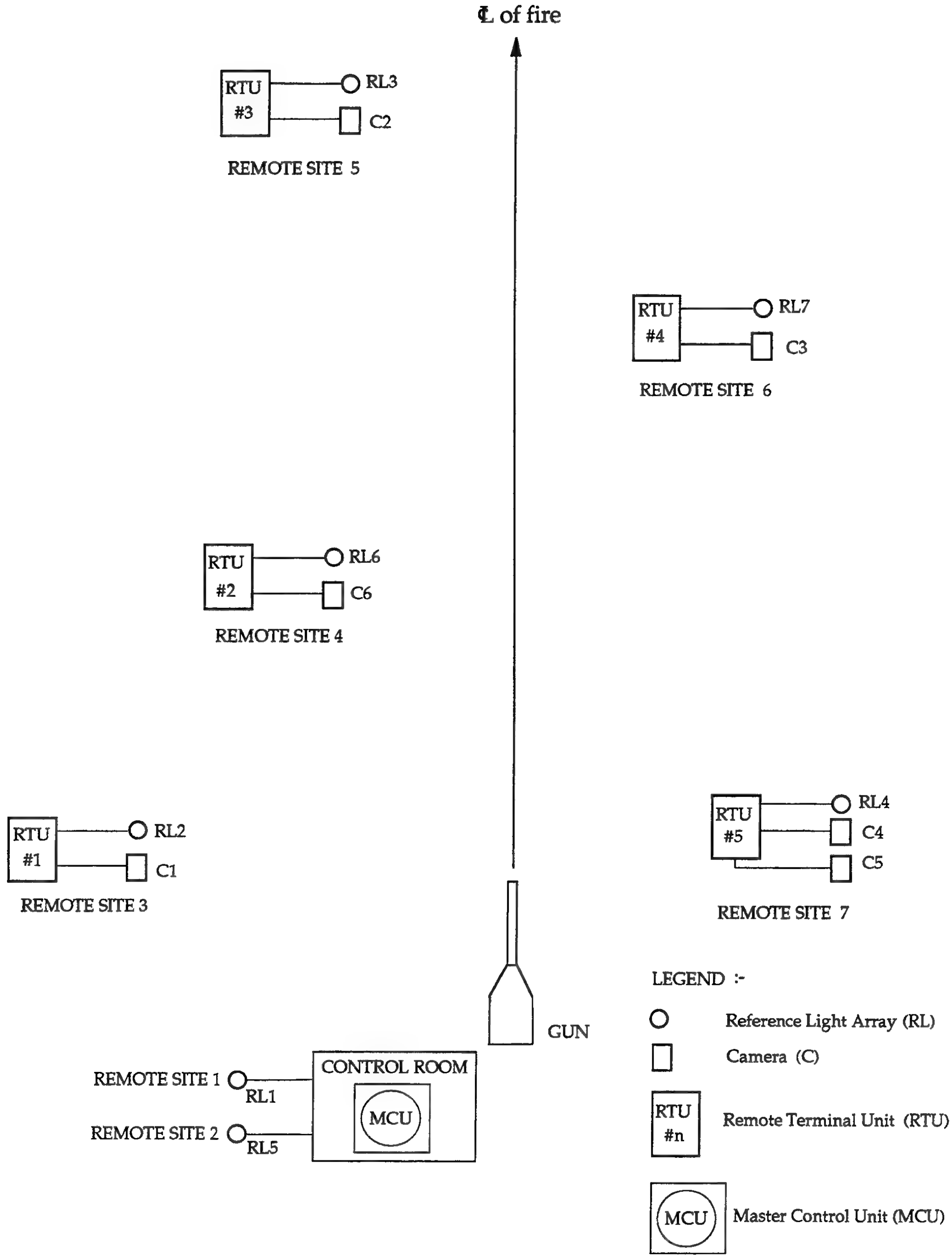


Figure 12. Port Wakefield Range - Remote Site Layout

2.3.2.1 Master Control Unit

The MCU is provided with a mimic panel, shown diagrammatically in Figure 13, which displays the status of each RTU and of the equipment operated by it. The top two rows of green and red light emitting diodes (LEDs) indicate the state of the camera shutters at each site. Any shutter which is open will cause the corresponding green LED in the top row to be lit. Similarly, any shutter which is closed will result in the corresponding red LED in the second row to be lit. A similar arrangement applies with the RL array status indication LEDs in the third and fourth rows. The bottom row of yellow LEDs indicate the RTU status. Any RTU which fails to respond to a status interrogation from the MCU will cause the corresponding yellow LED to be lit, indicating that RTU to be faulty.

Push to Test facility

The operation of the RTUs can be tested at any time by operating the Push to Test pushbutton on the front panel of the MCU, which causes the MCU to send a global command to all sites, requesting their status. This command does not cause any change of state on the RTU outputs.

Sequence Input External/Manual On

The telemetry system has a programmed control/timing sequence which is initiated either manually by moving the Sequence Input switch on the MCU front panel to the Manual On position, or by an input signal from the Main Sequencer when the Sequence Input switch is in the External position. When either the Main Sequencer signal input goes high, or the switch is in the Manual On position, the green LED next to the switch will be lit.

It is important to note that once initiated, the control sequence will continue automatically until completed, and cannot be interrupted or halted. Consequently, any testing of the system must be carried out prior to loading film in the range cameras.

Initial Power On condition

When the MCU is first powered On, all red and all yellow LEDs will be lit on the front panel. This is a default condition only, and the Push to Test pushbutton must be operated to determine the current status of each RTU.

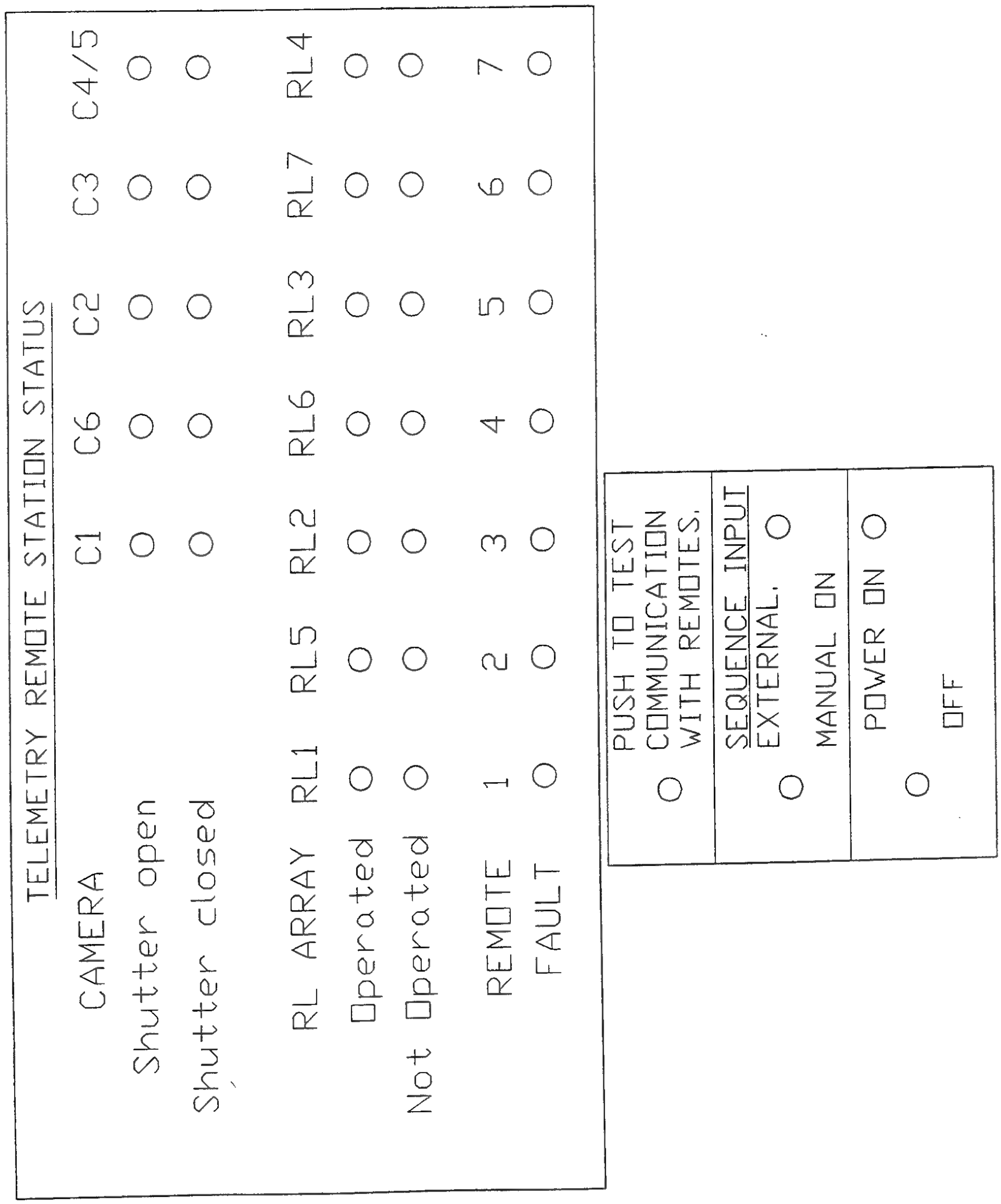


Figure 13. Mimic Panel

2.3.2.2 Remote Terminal Units

Each RTU consists of a small pole mounted weatherproof enclosure which houses all the telemetry equipment, including the antenna. The RTUs have no operator controls and only require two quick connect plugs connected to the site equipment cables for the units to be powered up and ready to operate. A red LED on the front panel provides Power On indication.

All RTUs are provided with 2 Digital Outputs (DO1 and DO2), and 2 Digital Inputs (DI1 and DI2), apart from RTU#5, which has 2 Digital Outputs (DO1 and DO2) and 3 Digital Inputs (DI1-DI3). The digital output and input designations are shown in Table 1.

Table 1: RTU digital output and input designations

RTU#	DO1	DO2	DI1	DI2	DI3
1 -4	Open/Close Cam shutter	Operate RL array	Cam shutter Status	RL array Status	–
5	Open/Close Cam shutter 1&2	Operate RL array	Cam shutter 1 Status	Cam shutter 2 Status	RL array Status

2.3.2.3 Timing Sequence

When the Sequence Input switch on the MCU front panel is moved to the Manual On position, or when the input signal from the Main Sequencer goes high with the Sequence Input switch in the External position, the MCU transmits a global command to all RTUs, which then carry out a programmed sequence of commands (independently of the MCU), with the timing shown in Table 2. The MCU polls each RTU at predetermined intervals during the sequence in order to update the status of the remote site equipment. If all RTUs and other site equipment are operating correctly, the MCU Mimic Panel display will be as shown in the Table.

Table 2: Telemetry Link timing sequence

TIME*	EVENT	MIMIC PANEL DISPLAY
0	Command - Open Camera shutters	• All red LEDs On - Camera shutters closed, RL arrays not operated • All green LEDs Off • All yellow LEDs Off (throughout sequence)
0 - 5	• Camera shutters open • MCU polls all RTUs for status update of site equipment	Unchanged
5	Mimic Panel updates	• Camera red LEDs Off • Camera green LEDs On - shutters open • RL array red LEDs On - arrays not operated • RL array green LEDs Off
15	Command - Operate RL arrays	Unchanged
15 - 20	• RL arrays operate • MCU polls all RTUs for status update of site equipment	Unchanged
20	Mimic Panel updates	• Camera red LEDs Off • Camera green LEDs On - shutters open • RL array red LEDs Off • RL array green LEDs On - arrays operated
25	Command - Close Camera shutters	Unchanged
25 - 30	• Camera shutters close • MCU polls all RTUs for status update of site equipment	Unchanged
30	Mimic Panel updates	• Camera red LEDs On - shutters closed • Camera green LEDs Off • RL array red LEDs Off • RL array green LEDs On - arrays operated

*in seconds - referred to start of sequence

Notes on the sequence:

1. The Operate RL array command causes each RL array to flash at 1 second intervals for a set length of time (usually 2 - 5 seconds). The green "RL array operated"LEDs

on the Mimic Panel provide a latched indication which is cleared by resetting the RL array equipment at each site (this is done when the cameras are reloaded with film after each firing), and then operating the Push to Test pushbutton on the front panel of the MCU.

2. Both the MCU and the RTUs are microprocessor based, and can be reprogrammed if required to provide different sequence timing from that shown above.

2.3.2.4 Interface between RTUs and remote site equipment

A typical remote site, showing equipment interconnections, is shown in Figure 14. The RTUs are mounted on the poles which support the RL arrays. The RTUs are fully weatherproof, and are usually left in position between trials.

A schematic circuit of the RL Control/Battery Box, which operates the RL arrays and provides power to the RTU, is shown in Figure 15. The Trigger circuit, which can be operated locally or remotely, switches 12 V d.c. to the array for a set length of time (adjustable between 2 and 5 seconds). The array consists of 3 xenon beacons which flash at a 1 Hz non-synchronised rate while the 12 V d.c. is applied. The change in voltage across a 20 ohm resistor, connected in series with the centre beacon, is detected by the Sense circuit input. As it is not critical that the outboard beacons flash, nor that any of the beacons flash more than once, to reduce complexity of the Sense circuit only the initial operation of the centre beacon is detected.

Prior to each trial, the RL arrays, RL Control/Battery Boxes and CCUs (with associated 24 V d.c. battery packs and vacuum pumps) are taken to each site, and the interconnecting cables connected as follows:

<u>1. RL Control Box to RL array</u>

This cable supplies the power required for operation of the array. When DO2 of the RTU goes low, or when the Trigger pushbutton on the front panel of the RL Control Box is operated, 12 V d.c. is switched to the array. When the RL Control Box Sense circuit detects the initial flash of the array centre beacon, its output goes high, placing 12 V d.c. on RTU DI2. A green LED on the RL Control Box front panel is also lit, to a provide a local indication. This LED will remain lit until the circuit is reset.

<u>2. RL Control Box to RTU</u>

This cable carries command and status signals between the RL Control Box and the RTU, and power from the RL Control Box to the RTU. One end of this cable is terminated in a 9-pin plug which connects to socket R on the RTU. The other end is terminated in a 4-pin plug which connects to the RL Control Box.

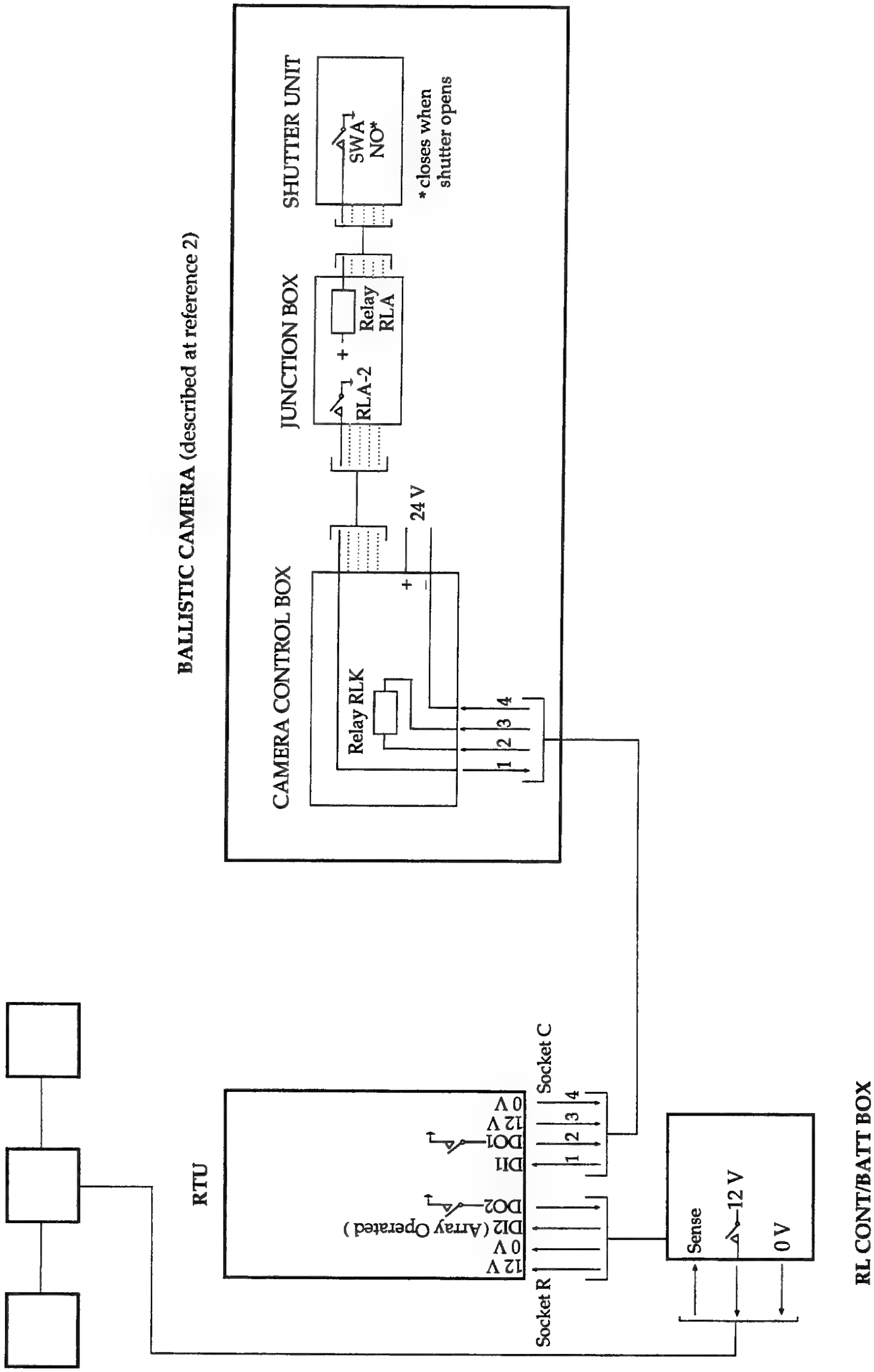


Figure 14. Remote Site Interface Arrangement

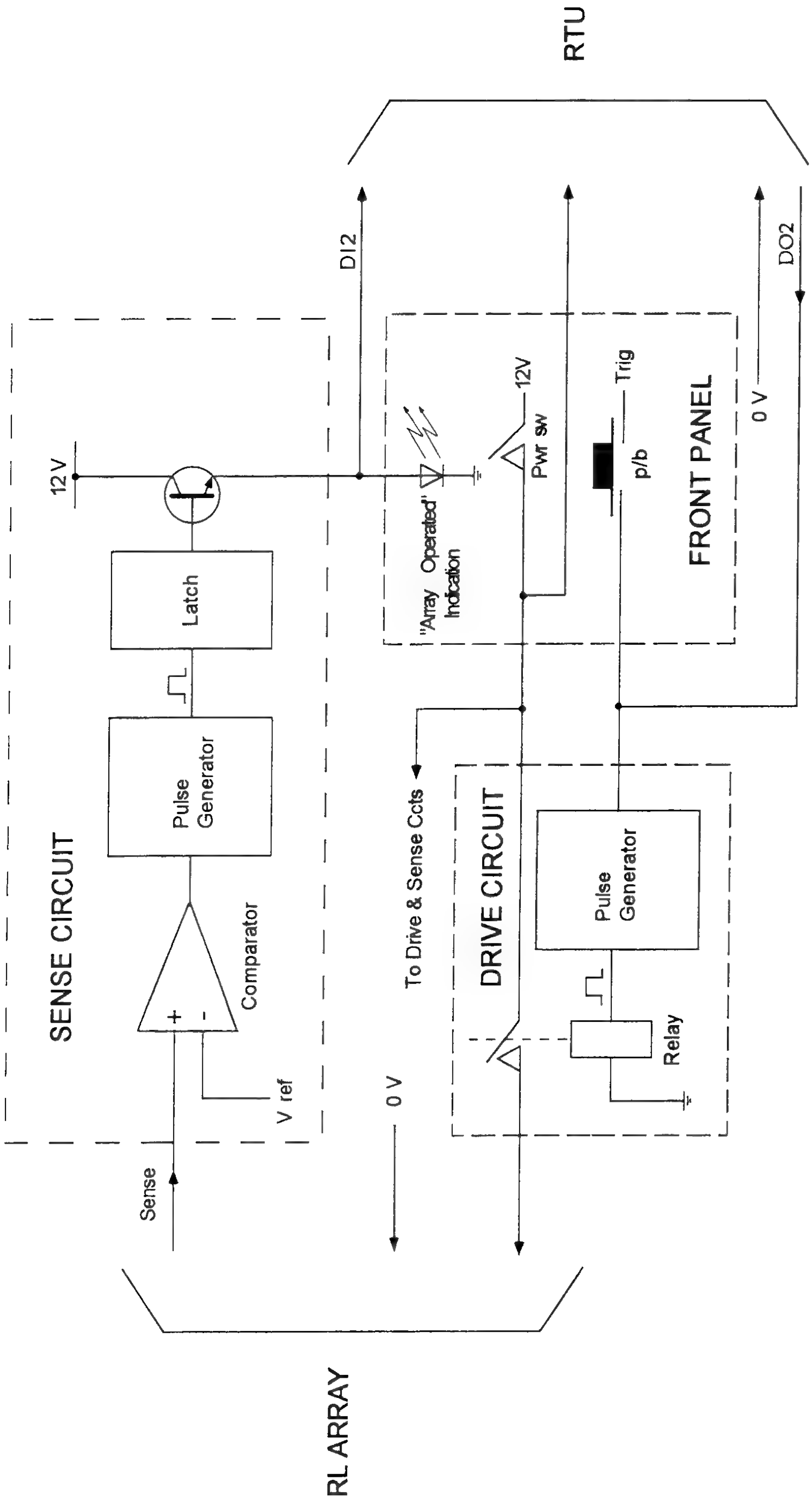


Figure 15. RL Control/Battery Box - schematic circuit

3. RTU to CCU

This cable carries command and status signals between the RTU and CCU, and switched 12 V d.c. to the relay in the CCU which controls remote operation of the camera shutter unit. The cable also carries the common 0 V line between the RL Control Box 12 V battery supply and the CCU 24 V battery supply. The cable is terminated at one end in a 9-pin plug which connects to socket C on the RTU. The other end is terminated in a 12-pin socket which connects to the Control plug on the CCU. When RTU DO1 goes low, or the shutter control switch on the CCU is moved to the Open position, a 24 V pulse is applied to the shutter unit. When the shutter opens, RTU DI1 is connected to 0 V via a microswitch contact in the shutter, to provide the indication that the shutter has opened.

3. Trials Procedure

In order to minimise overexposure of the camera film due to any residual ambient light, the first test vehicle of the night is not usually launched until aproximately 1.5 hours have elapsed after sunset, unless conditions are exceptional (for example heavy cloud cover), in which case it can be launched earlier. Atmospheric conditions are not critical, but ambient temperature, atmospheric pressure, wind speed and direction are all recorded for each trial. Persistent rain may force a trial to be aborted as moisture is a problem with operation of the cameras. It is unusual for more than four trials to be scheduled for one night, due to gas availability (this depends on launch pressures specified) and/ or gun pressurization times, camera cartridge/film holder availability and time constraints.

3.1 Preparation

Prior to carrying out a trial, the following procedures and tests are required to be observed:

1. Prepare the site in accordance with the appropriate Propulsion Data Sheet (PDS). For the Edinburgh range refer to PDS#273, and to PDS#291 for the Port Wakefield range.

2. Set up and test the range instrumentation, consisting of the RL arrays, ballistic cameras and associated control units.

3. Port Wakefield range only - Conduct a communications test between the telemetry system Master Unit and the Remote Terminal Units.

4. Set up and test the Muzzle Velocity Measurement System as detailed in Technical Memorandum WSRL-0522-TM.

5. Where operators are stationed at remote camera and/or RL array positions, provide a portable radio at each position and conduct a radio communication check with the base station, located in the Control Room.

6. Connect on-board power to each test vehicle for trial, and test operation of the strobe units using the test switch provided.

7. Port Wakefield range only - Arrange with P&EE nightwatchman for range background lighting to be switched off during the trial.

8. Port Wakefield range only - Close off all range access roads crossing line of fire.

3.2 Conduct of Trial

Upon completion of all procedures and tests, and when ambient light level has fallen to an acceptable level (and assuming weather conditions are suitable), as determined by the Officer -in-Scientific-Charge (OISC), final preparation for the trial can commence. At this stage the gun can be loaded, elevated and pressurised, while as a concurrent operation the film loading procedure for the cameras is conducted under the direction of the Camera Control Officer (CCO).

When the required gun reservoir pressure has been attained and the all clear has been received from the CCO, perform the following procedures/checks immediately prior to commencing the countdown sequence:

1. Edinburgh Range only - Obtain clearance from RAAF Control Tower

2. Pt.Wakefield Range only -Advise P&EE nightwatchman that trial is imminent.

3. Close gates to compound.

4. Pt.Wakefield Range only - Confirm that all background lights have been turned off.

5. Check that site is clear of personnel.

6. In cases where additional ground instrumentation is being provided, advise any personnel required to operate this equipment that countdown sequence is about to commence.

7. Confirm gun pressure correct.

8. Port Wakefield Range only - check that Sequencer (see section 3.2.1) is reset to seconds and is in the "Held" state.

9. Check that Muzzle Velocity System is showing an "armed" indication - if it is showing a "fired" indication it will need to be rearmed.

3.2.1 Countdown Sequence - Port Wakefield Range

The Main Sequencer, located in the Port Wakefield Control Room, has 14 output channels which can each be programmed to switch between a low (0 V) level and a high (24 V) level at specified times during the countdown sequence.

The sequence is initiated at 60 seconds prior to time zero (gun fire), and continues until the Stop pushbutton on the front panel is pressed. 5 channels of the Sequencer are currently connected and configured to control the operation of various events during the sequence. These events, marked with an asterisk, along with those carried out manually by an operator, are detailed in Table 3.

Table 3: Port Wakefield Countdown Sequence

Time (s)	Event
-60	*Switch on range warning beacon Advise gun site instrumentation operators “Starting Sequence, -60”
-50	Operate gun arming key
-40	*Switch off gun site floodlights
-30	Advise operators of gun site instrumentation “-30”
-20	Check Muzzle Velocity System showing “armed” indication
-10	*Initiate Telemetry System sub - sequence (refer Table 2)
	Advise operators of gun site instrumentation “-10”
-5	Abort sequence if all green Shutter Open LEDs on Telemetry System MCU Mimic Panel are not lit
0	*Gun firing pulse
+5	*Operate RL arrays 1 and 5

Note - Events marked by asterisk are controlled by Main Sequencer

3.2.2 Countdown Sequence - Edinburgh Range

As no Sequencer is provided at this range, all events during the countdown sequence, including firing of the gun, are carried out manually. It is also necessary, unlike at the Port Wakefield range, to manually record gun and meteorological data just prior to gun fire. Accordingly, there is some variation in the countdown sequence compared with that at the Port Wakefield range, as follows:

Table 4: Edinburgh Countdown Sequence

Time(secs.)	Event
-60	1) Radio call - Control to camera operator C5: "-60 and counting, acknowledge please"
	2) Turn on range warning light
	3) Advise operators of site instrumentation (where applicable) "-60 and counting"
-40	1) Turn on RL array power supply
-30	Advise operators of site instrumentation "-30"
-15	1) Radio call - Control to camera operator C5: "-15, open shutters"
	2) Move Control Panel camera shutter switch to "Open" position
-10	1) Turn off gun site floodlights
	2) Advise operators of site instrumentation "-10"
-5	1) Check Muzzle Velocity System showing "armed" indication
	2) Record gun reservoir pressure and all meteorological data
0	Operate gun Fire pushbutton
+5	Operate Control Panel Trigger RL arrays pushbutton
+10	1) Radio call - Control to camera operator C5: "Close Shutters"
	2) Move Control Panel camera shutter switch to "Close" position
+20	Turn off RL array power supply

Notes on the above sequence:

1. It is very important to establish the integrity of the radio communication link to C5 at the time of commencing the sequence, as failure of the camera operator to respond to the "open shutter" command due to poor communications can seriously jeopardise the results of a trial.

Accordingly, the sequence is to be aborted if acknowledgment has not been received from the operator at C5 prior to the -30 second mark of the sequence.

2. Not withstanding a positive response to the radio link check, instances have occurred where the operator has failed to respond to the "open shutter" command later in the sequence due to intermittent communications. In case of such an occurrence, where the operator does not hear the "open shutter" command, the following event of the floodlights being switched off is to be taken as the alternative signal to open the camera shutter.

3. It is important that radio silence be observed between -10 seconds and time zero, so that in the event of a malfunction leading to a camera shutter failing to open, the camera operator is able to notify Control in sufficient time for the sequence to be aborted.

3.3 Post Trial Procedures

1. When all firings have been completed, carry out the specified procedures contained in the relevant PDS's with respect to the gun site and range equipment/instrumentation.

2. Port Wakefield Range only - Advise P&EE nightwatchman that trial has been completed.

3. Edinburgh Range only - Advise RAAF Control Tower that trial has been completed.

4. On the day following the trial, recover from the range all firing hardware from the trial. This will consist of the test vehicles, model sabots, pusher sabots, and, in the case of the transonic gun, the firing pistons or piston valves. The X and Y co-ordinates of the position at which each item of hardware was recovered should be noted in a logbook for future reference.

4. Reading and Preliminary Processing of the Camera Film Images

The hardware and software used in this process are fully described in reference 3. The following sections provide a brief summary.

4.1 Digitisation

The camera films are first processed to produce negatives, following which each negative is mounted in an optical comparator (or co-ordinate measuring instrument) for the purpose of digitising the images. A typical ballistic camera film negative, showing nose and tail strobe unit images, is shown in Figure 16. A video camera displays the images on a TV monitor at such a magnification as to clearly display the detail necessary for accurate, reproducible readings to be obtained.

As each image is read, the X and Y co-ordinates are displayed on two six digit readout units, and are also directed to an IBM compatible personal computer (PC) via a computer interface card, which acquires the co-ordinates when the operator presses a button or foot pedal.

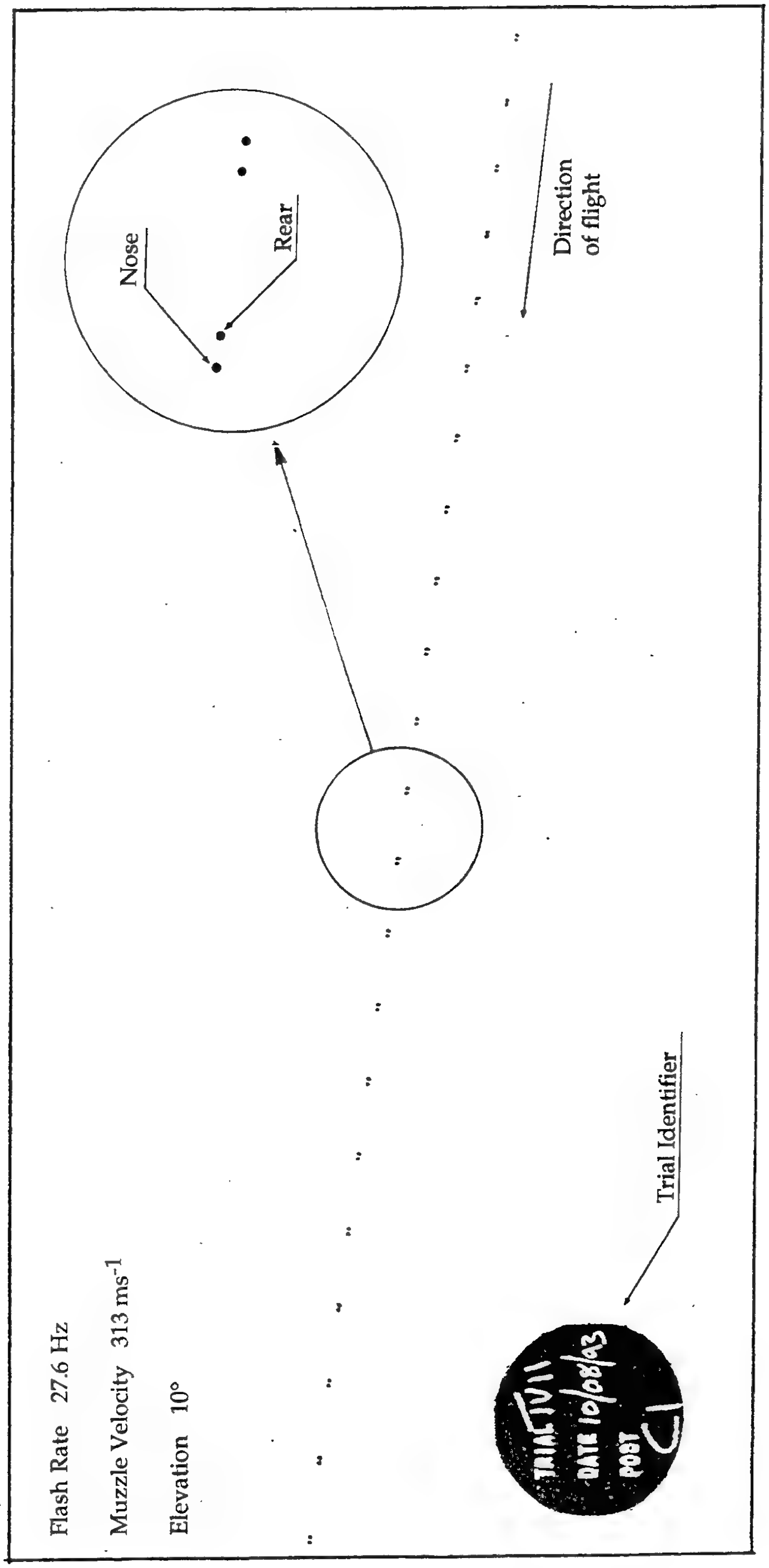


Figure 16. Camera Film Negative

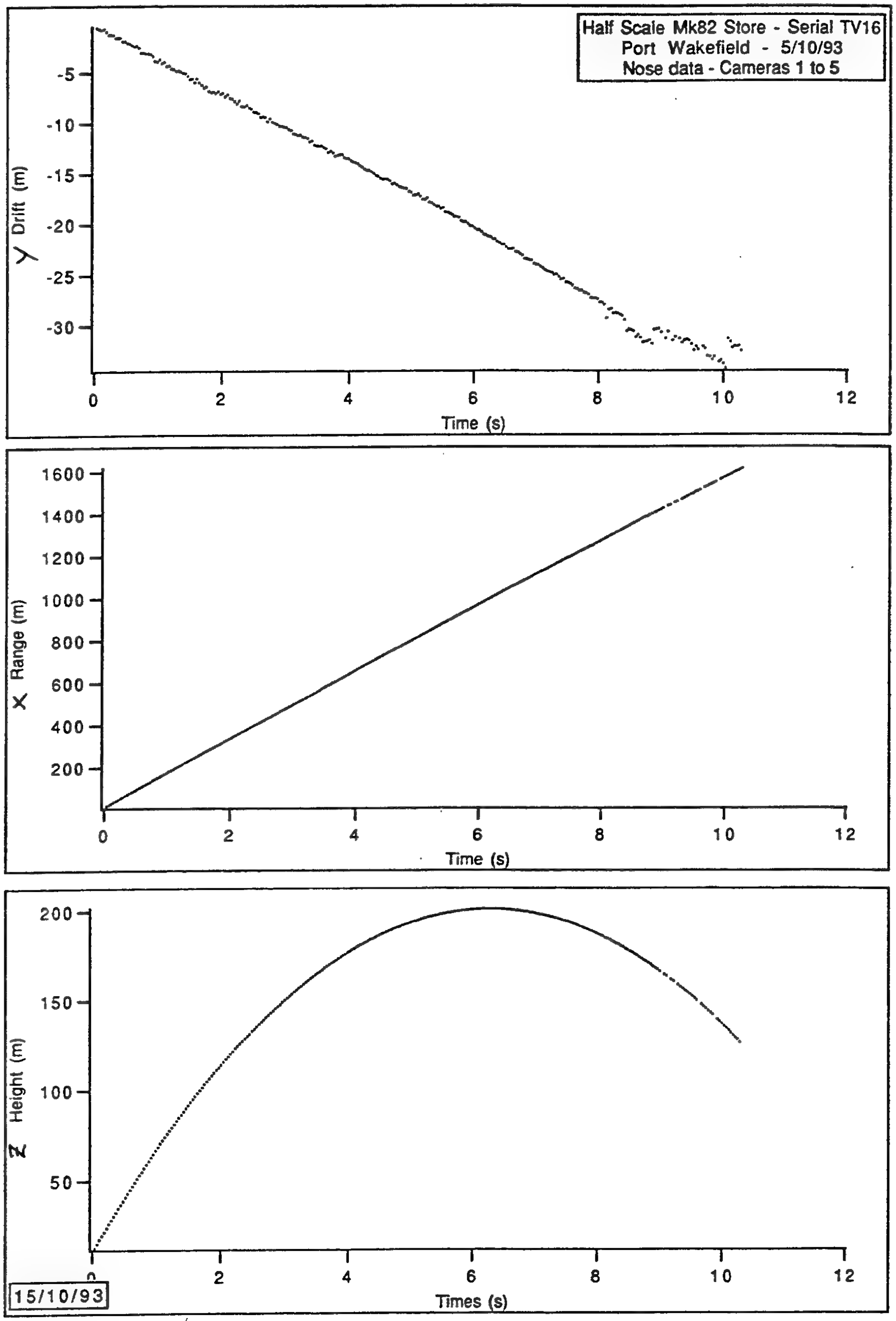


Figure 17a. Height, Range and Drift as a function of time for nose strobe unit

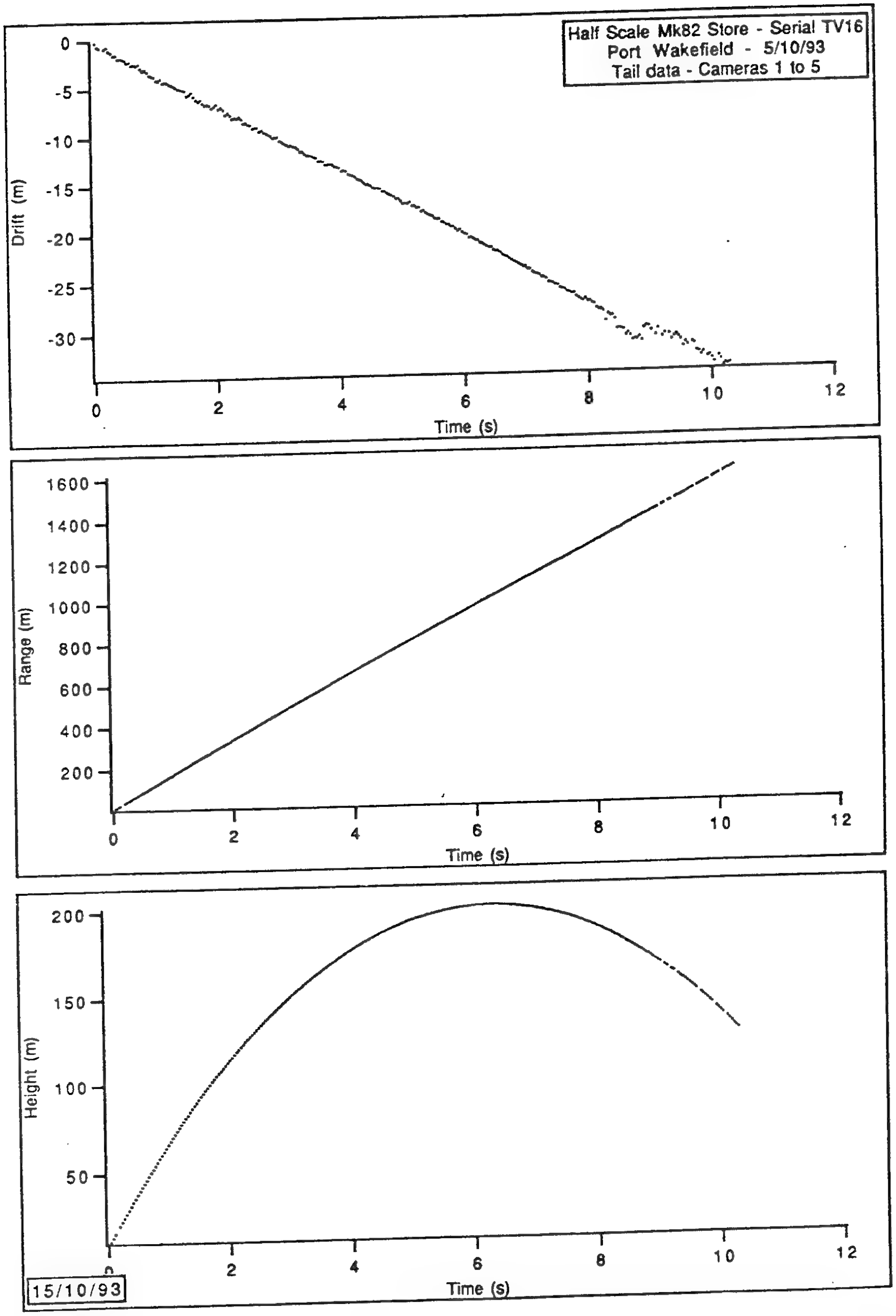


Figure 17b. Height, Range and Drift as a function of time for rear strobe unit

4.2 Derivation of Azimuth and Elevation Angles

When all the image co-ordinates from a camera film have been read into the PC, the data file created is processed to obtain azimuth and elevation angles corresponding to each image reading. This process is then repeated for the next camera film. When all films have been read, the next procedure is to match readings from all the cameras.

4.3 Calculation of Trajectory

The information from all cameras is combined to obtain a solution for the position of each image, and hence the range, height and drift of the model against calculated flight time. Time information is computed from the flash rate of the strobe unit.

An approximate solution is first calculated. This is then used as an initial estimate to start the iterative procedure to find a least squares solution providing an estimate of the image position which minimises the sum of the squares of the elevation and azimuth residuals for each camera.

4.4 Aerodynamic Coefficients

The aerodynamic coefficients are estimated using the maximum likelihood parameter estimation technique (references 4 and 5). The technique attempts to find the values for parameters characterising the mathematical model such that the sum of the squares of the differences between the model output (predicted response) and the input (observation vector) is minimum. The input vector is the attitude angles of the projectile (pitch and yaw) and the three components of the velocity of the centre of gravity of the projectile.

The aerodynamic forces and moments can be expressed in terms of linear or non-linear aerodynamic coefficients which are functions of angle of attack and Mach number. The definition of these aerodynamic coefficients dictates the complexity of the model.

5. Results

This technique has been in routine use for quite some time now, and is currently been used for providing experimental flight data for various configurations of the Mk82 and Mk84 General Purpose Low Drag bombs which form part of the stores inventory of the RAAF F-111C and F/A-18 aircraft. This program of work has involved a series of trials over a range of Mach numbers varying from 0.5 to 1.3.

Typical trajectory graphs showing height, range and drift as a function of time for the nose and tail strobe units are shown in Figure 17. Full details of the trials results

obtained and subsequent analysis and determination of aerodynamic coefficients can be found in reference 6.

To date a total of 63 half-scale models of the bombs have been launched, with a high launch survivability rate being achieved. The on-board instrumentation failed at launch on only 2 occasions. One failure was due to the collapse of the rear section of the model in the gun barrel, which allowed a fixing bolt to move forward and spear through the electronics package. This problem has since been rectified by strengthening those rear section components identified as being responsible for the failure, as detailed in reference 7.

The other failure resulted from a suspect solder joint on a printed circuit board which, when subjected to launch stresses, provided a low resistance path between adjacent tracks on the board. This prevented sufficient voltage being applied to the strobe tubes for them to operate.

There have been a very small number of cases where either the front or rear tube has misfired intermittently throughout the flight duration, resulting in missing images on the camera film. However, as the rate of misfire was quite low, approximately 1 in 50, the co-ordinates of the missing images were able to be determined, with negligible induced error, by interpolation during the film reading process.

It was difficult to determine the cause of the misfires, as during pre-trial and post-trial tests (of the recovered models) none occurred, and flight conditions differ very little from those under which the tests were carried out. One possible explanation is that one or more cells in the battery pack of such a model may have developed a fault prior to or at launch, hence lowering the terminal voltage of the pack, although this cannot be verified as post-trial tests are necessarily carried out with a new battery pack or external power source (the original battery pack is destroyed on impact).

The images recorded on the camera films have generally been of good quality and clearly distinguishable from background "clutter", providing sufficient care has been taken during developing to minimise the effect of "graininess" on the film. On occasions film has not been correctly loaded into a camera, resulting in no images at all being recorded due to the camera being out of focus. Instances have also occurred where films have been damaged during removal from cameras or during processing, making the digitisation process difficult or even impossible. These occurrences have been infrequent, however, and as there is a degree of redundancy in this technique, have not had a marked effect on the overall results.

6. Conclusions

This report has described a method which has proven to be an effective and reliable means of obtaining data relating to the free flight behaviour of projectiles.

As discussed, the nose and tail mounted strobe units provide information from which the projectile trajectory and attitude during flight can be deduced, leading to an evaluation of the linear aerodynamic coefficients.

In some instances, as with the Mk82 bomb, it is necessary to conduct trials with scaled down models in order to facilitate gas gun launches, while in other cases the reverse may apply. For example a scaled up model of the 81 mm mortar is required so that the geometry of the model is sufficiently increased to accommodate both nose and tail strobe units at the minimum specified separation.

When trajectory information only is required and the size of the projectile being studied can be accommodated within the bore of the gas guns, it may in some instances be possible to launch an inert version by carrying out a simple modification, for example the removal of the nose fuze from the fuze well and its replacement with a nose strobe and associated instrumentation, able to be housed within the original fuze well. This saves considerable time and cost, as it eliminates the need to design and manufacture models of the projectile.

The dual strobe technique is restricted to applications with stable projectiles which exhibit a low angle of incidence to the line of fire. For unstable projectiles with a high angle of incidence, non-linear aerodynamic coefficients, arising from roll-pitch coupling effects, assume greater significance. These non-linear terms can be determined if data relating to the roll motion of the projectile and the lateral accelerations acting on it are available.

A means of achieving this, by the provision of accelerometers mounted on-board the projectile, is currently being evaluated. The accelerometers provide measurements from which roll motion can be derived, as well as a direct measurement of the lateral restoring moments acting on the projectile. A detailed description of this method and trials results so far obtained is contained in reference 8 .

It is eventually proposed to extend the dual strobe technique to incorporate the additional instrumentation associated with the accelerometers so that sufficient data can be obtained for a complete analysis of the flight behaviour of all projectile types to be carried out.

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19. ABSTRACT
A method has been developed for making very accurate position and angular attitude measurements over the trajectory of gun launched, fin stabilised weapons. The method has been extensively used for free flight testing of weapon models. This report describes the on board instrumentation, the range instrumentation and the experimental procedure used to carry out the trajectory measurements. The post trials processing of the camera records is also described and a brief account given of the analysis used to derive vehicle aerodynamics.